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HYDRAULIC CONTROL DESIGN
AND MODELING TECHNIQUES
FEBRUARY 1989

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This report details the analysis of a hydraulic actuator system. The analysis consists of designing control compensation by means of deriving a frequency response from a non-linear mathematical model and using classical control theory. This hydraulic actuator system will be used on the Turret Motion Base Simulator (TMBS) which is a unique six degree of freedom simulator being developed.

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## PREFACE

This report covers the analytical modeling of hydraulic actuator systems. It also details control design methodologies. This report may be difficult to read for the casual reader. It is written assuming the reader has some fundamental background in control theory.

I would like to thank Contraves Goerz Corporation for their notes descibing the hydraulic system which will be used on the Turret Motion Base Simulator (TMBS). Contraves Goerz Corporation is the prime contractor for the TMBS.

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## 1.0 INTRODUCTION

This report, prepared by the Systems Simulation and Technology Division, of the U.S. Army Tank-Automotive Command (TACOM) describes an analytical study of hydraulic systems used for laboratory testing. Motion base simulators are used by the Army to test vehicles or vehicle subsystems for various forms of performance and structural integrity. This form of testing is performed by hydraulic systems which produce forces applied to the vehicle simulating operation over terrain profiles.

A considerable effort is being made to develop analytical models of laboratory simulators so that a complete assessment can be made before testing is conducted. Analytical studies may point to various problems with the system and control design considerations may be made early in the development stage. The results of selected command signals representing terrain profiles can be simulated with the analytical model before being applied to the actual system. As the level of complexity in laboratory testing is increased the more important becomes analytical studies.

The Turret Motion Base Simulator (TMBS) will be a very complex system used for laboratory simulation testing. The TMBS is a computer controlled 6 degree of freedom motion base simulator which is capable of driving an M1 turret. An effort is being made to model the entire TMBS system. The starting grounds is to develop a model of a hydraulic actuator system and a means of control design and evaluation of performance. Although the model used in this report describes the hydraulics, it only contains a single actuator while the TMBS consist of a six actuator system. Therefore, the results in this study may not describe the performance of the TMBS. At this initial stage of the TMBS development, the material presented in this report should only be considered a study of a general hydraulic system. The analytical study that more directly relates to the TMBS will be addressed at a later time when the entire system is modeled. A portion of a model describing the dynamics and kinematics for the TMBS has already been established. The results of this study will be be incorporated in the model in the near future so that a model will be constucted that contains the six actuator systems coupled with the platform dynamics.

This is a first attempt in modeling hydraulic systems in detail. An earlier attempt was made in creating an empirical model based strickly from test data which is described in reference 1. This technique consisted of a curve fit model of a hydraulic system derived from a measured closed loop frequency response of the system. Although this technique had resulted in prediction of actuator motion to some degree, it was only good for a system with no modifications or complexity.

## 2.0 OBJECTIVE

This report contains the initial stage of an analytical study of the TMBS. The primary objective is to develop a hydraulic actuator model along with a control design which produces reasonable performance. It is expected that the actuator system will have a performance bandwidth of 10 Hz with an adequate stable transient response. The initial step in achieving this objective is to find a means of designing a control system by using the mathematical model. A methodology was developed which consisted of writing a FORTRAN program which is used to design control system compensation by supplementing it with the computer mathematical model.

## 3.0 CONCLUSIONS

The methodology and software developed to design control compensation seems to work very well. There is definitely a correlation between the stability margins obtained in the frequency domain and the transient response in the time domain. The model shows that the actuator system can perform a 10 Hz bandwidth. The step response simulated has very good results in terms of overshoot and settling time. It is concluded that a control design can be obtained analytically without making a linear reduction of the system.

The control design obtained through this analysis may or may not be adequate for the actual system. This will depend solely on how accurately the hydraulic model compares with the real system. The most serious difficulty encountered while modeling a hydraulic system is that several of the parameters required to describe the system are unknown. What is more important at this time is that the methodology is now available for control design if an adequate model can be obtained. The ground work established in this study can lead to the analysis of other hydraulic systems used for laboratory testing or for any other application. Deriving the frequency response from a non-linear mathematical model can assist in control design or improvementing existing control designs.

The study presented in this report is a starting point for more extensive analytical studies of hydraulic systems. A model of the TMBS has been established containing the dynamics and kinematics which consist of the configuration of the 6 actuator orientation and platform. However, this model required a working model of a hydralic actuator with control. Now that a working hydraulic actuator model has been established, the next step is to incorporate the hydraulic model into the TMBS model. The study will lead to investigating the control of the platform by the six actuators. Various methodologies have been developed by Contraves Goerz Corporation which uncouples the effects of the six actuators driving the platform. These methodologies consist of a form of adaptive control which involve considerations of the inertias, mass and actuator/platform orientations in 3-dimensional space. This form of adaptive control, supplements with the single actuator control to complete a control design for the entire system. Future goals are to investigate these methods thoroughly by using analytical models which may lead to problem solving or possible improvements with the TMBS system.

## 4.0 RECOMMENDATIONS

It is important to validate the hydraulic model developed in this study. At this time it can be stated that the model exhibits behavior very similar to other known hydraulic systems. The pressures, flow rates and actuator/valve characteristics of the model are reasonable for this type of system. Nevertheless, there is a degree of uncertainty to the parameters used for the model. Contraves Goerz Corporation is scheduled to perform a single actuator test later this year. At this time the model can be validated and adjusted if necessary. The analysis and control design were conducted using a small mass for a load. This was done so that comparisons can be made with the single actuator testing using little to no load as a starting point.

The search for an optimal control design was not real extensive at this time. Once the model shows some validity then an extensive optimal control design can be studied. This is only when the unknown parameters can be determined and the proper configuration is known. (There are still uncertainties on the inner loop configuration). Once this is accomplished a further study can be made on optimizing the controller for a loaded case consisting of a larger mass.

## 5.0 DISCUSSION

The starting point for modeling hydraulics is to obtain a set of equations which best describes the system. These equations contain many parameters which reflect the characteristics of the system. These parameters are not always known and must be estimated or guessed at some way until measurements can be made on the system. It may not be possible to measure some of these parameters directly. Some parameters may require determination by a combination of measurements and other known mathematical relationships. Once a set of equations and parameters are obtained, a model can be developed. There are many forms of computer software available to simulate the model. The one used for this analysis is the Advanced Continuous Simulation Lanquage (ACSL) which basically simulates equations in the time domain.

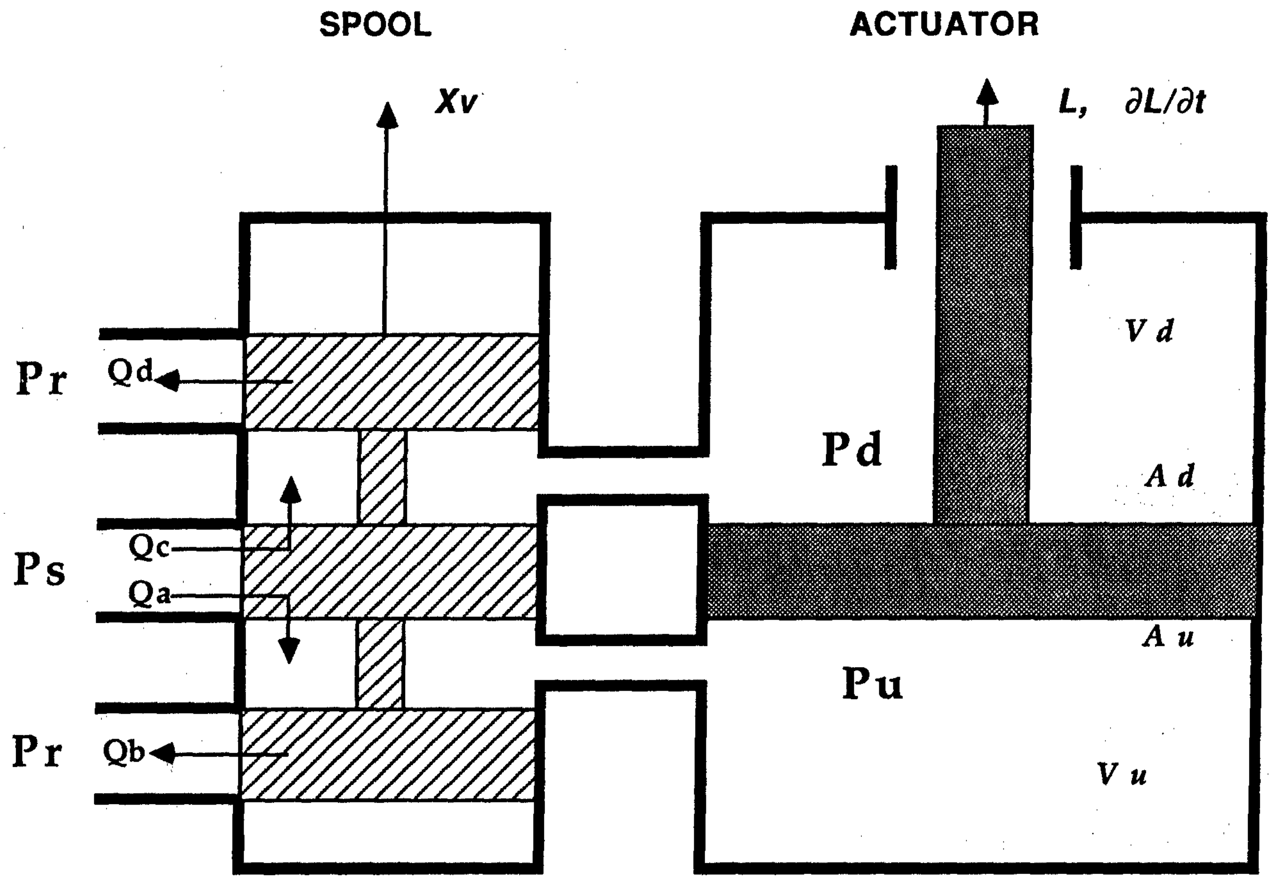
To achieve the results of a system with feedback control, a control design must be known or derived from the model. A control design is part of the system that is modeled and comprises the loop configuration and control compensations. For our case, the control design received was from early development and is not considered acceptable. A good part of this study is to find a means of deriving a control design from an analytical model.

To derive a control design, the proper method using classical control theory implies that various frequency responses must be determined where an open loop response can be evaluated and control compensation can be designed. Most fundamental courses in control theory stress the importance of linearizing the system equations (Plant equations). This is done so that the frequency response can be easily obtained because the equations reduce to transfer functions in simple Laplace Transform format. With a linearized set of equations it is also convenient to determine the eigen-values (root locus analysis). It is usually questionable when linearizing a system if the end results are still truly representative of the system. An effort was made in this study to develop a software technique which will determine a frequency response from a non-linear mathematical model directly without linearizing. The primary philosophy was that no questionable linearizing techniques have to be applied and the procedure of algebraically reducing the system equations to a transfer function was not required. This method takes advantage of number crunching computer power and is similar to a frequency response technique which is measured in a laboratory utilizing a signal analyzer. The hydraulic model is then evaluated with this technique and control compensation is designed for each feedback loop. The rest of this report describes the details of the hydraulic model and the results of the analysis used for this technique.

### 5.1 HYDRAULIC MODEL

Shown in Figure 5-1 is a diagram illustrating the internal workings of a hydraulic spool/actuator system. The spool basically controls the fluid flow to the actuator and is considered the input state to these equations. As the spool is displaced up, the supply pressure creates flow to the actuator bottom chamber which creates a pressure (Pu) which in turn produces an upward force on the actuator. The negative actuator motion is produced the same way with a spool displacement down. The equations describing the spool/actuator system are shown in Table 5-1. The model is a simplified case where no overlaps are considered for the spool or the actuator.

# HYDRAULIC ACTUATOR SYSTEM




**INPUT:** Xv Spool Position

**ACTUATOR:**
L Actuator Position
∂L/∂t Actuator Velocity

Au , Ad Effective Actuator Area

Vu , Vd Entrained Volume

**PRESSURES:**
PS Supply Pressure
Pr Return Pressure
Pu Actuator Pressure Up
Pd Actuator Pressure Down

**FLOWS:**
Qa Flow In from Supply (Actuator Up)
Qb Flow Out to Return (Actuator Up)
Qc Flow In from Supply (Actuator Down)
Qd Flow Out to Return (Actuator Down)

FIGURE 5-1

# HYDRAULIC EQUATIONS

## Assume Ideal Valve with Zero Overlap

Flow Area $= \pi D X_v = W X_v$

Flow $Q = C X_v \sqrt{\Delta P}$

Where C is hydraulic constant

$C = C_d W \sqrt{SQRO}$

| | |
|---|---|
| D | Spool Diameter |
| Xv | Spool displacement from null |
| Q | Flow |
| ΔP | Pressure across valve/actuator |
| W | Valve Spool Circumference |
| SQRO | Fluid Constant |
| Cd | Hydraulic Constant |

## Valve Displacement

**Valve Up Xvu**

$Xvu = Xv$ if $Xv > 0$
$= 0$ if $Xv < 0$

**Valve Down Xvd**

$Xvd = |Xv|$ if $Xv < 0$
$= 0$ if $Xv > 0$

## Flow Equations for Valve/Spool/Actuator System

$Qa = C\, Xvu \sqrt{|Ps - Pu|}\ \text{Sign}(Ps - Pu)$

$Qb = C\, Xvd \sqrt{|Pu - Pr|}\ \text{Sign}(Pu - Pr)$

$Qc = C\, Xvu \sqrt{|Ps - Pd|}\ \text{Sign}(Ps - Pd)$

$Qd = C\, Xvd \sqrt{|Pd - Pr|}\ \text{Sign}(Pd - Pr)$

Pu Actuator Pressure Up
Pd Actuator Pressure Down
Ps Supply Pressure
Pr Return Pressure
Qa, Qc Flow In from Supply
Qb, Qd Flow Out to Return
(Actuator Up Down Respectively)

## Actuator Pressure

$\partial(Pu)/\partial t = \beta / Vu\ (Qa - Qb - Au\, \partial L/\partial t)$

$\partial(Pd)/\partial t = \beta / Vd\ (Qc - Qd - Ad\, \partial L/\partial t)$

where

$Vu = Vu0 + Au\, L$

$Vd = Vd0 - Ad\, L$

ß Bulk Modulus of Fluid

Au, Ad Actuator Piston Area
(for up and down respectively)

Vu0, Vd0 Initial Entrained
Vu, Vd Entrained Volume
(for up and down respectively)

L Actuator Displacement

∂L/∂t Actuator Rate

## Actuator Force

$F = Pu\, Au - Pd\, Ad$

F Actuator Force

TABLE 5-1

The direction of the valve displacement is detected and separated by the variables Xvu & Xvd for up and down motion respectively.
This was done so that the up and down cases can be handled separately since the two motions have different characteristics in terms of flows, effective areas and entrained volumes. Note the u & d subscripts for the remaining equations. There are four relative pressure drops between the supply & return (Ps & Pr) and the actuator pressures (Pu & Pd). The four relative pressure drops produce four flows which are described in the equations as Qa, Qb, Qc and Qd. (See Figure 5-1) The flow is assumed to be proportional to the spool displacement (Xv) times the square root of the corresponding pressure drop by a constant C. The equations take the absolute value of the pressure drops since complex numbers do not apply (square root of a negative value). The sign of the pressure drop is considered by the 'SIGN' function instead. Thus a negative relative pressure drop creates a negative flow. The spring characteristic of fluid is affected by the entrained volumes (Vu, Vd, Vu0 and Vd0) and the bulk modulus (ß) which is assumed to be constant (no temperature variation). The derivative of pressure is dependent on many quantities including the actuator motion. In a sense this can be considered a natural internal feedback in the system. Reducing these equations to a single transfer function is very difficult and is not required for the methodology presented in this analysis. The valve transfer function is shown in Table 5-2 which describes the valve dynamics by a second order. The S represents Laplace Transform notation throughout this report. This equation describes the response for a valve where the input would be current and the output is the displacement of the spool. Also shown in Table 5-2 are the various parameters used for the model. The most questionable and difficult to measure value is the constant C which is the hydraulic flow constant mentioned earlier. The various equations were obtained partially from a combination of reference 2, 3, and 4. The parameters used for this analysis are from reference 4. The key element of control is the feedback loops which can now be incorporated with these equations describing the system to complete the model. The model was computer simulated using Advance Continuous Simulation Lanquage (ACSL) which is listed in Appendix A.

It should be mentioned that this hydraulic model is a simplified representation. There are many nonlinear hydraulic fluid flow properties which are assumed to be negligible in this model. In addition this model describes a two stage servo system even though it is believed the TMBS will have a three stage servo system. Since no details have been received on the pilot valve characteristics it will be assumed that the pilot valve is an ideal case. It is also proposed that the TMBS will have three valves driving each actuator which are all controlled in the same manner. This was primarily done for safety and backup considerations. It is also assumed that this will not change the actuator performance predicted by this model. Some of the assumptions made to simplify this model may not be valid. These modifications may be incorporated in the model at a later time.

## 5.2 METHOD FOR DETERMINING A FREQUENCY RESPONSE

The basis of designing a control system using classical control theory is to obtain a frequency response of the system (Plant Response). Once a frequency reponse is established, control compensation can be designed to desired stability margins and gain crossover (bandwidth) which will reflect the system's performance in the time domain. As mentioned earlier, an effort was made not to complicate the analysis with questionable linearizing techniques which simplify but may burden the accuracy of the analysis.

# System Parameters Used In Modeling

## Valve Transfer Function

$$\frac{\text{Spool Position}}{\text{Input Current}} = \frac{1.5\text{ E-4}}{2.533\text{ E-6 } S^2 + .002228\ S + 1} \quad \frac{\text{IN}}{\text{mA}}$$

Circumference W = 3.78 IN

## Actuator

Initial Entranined Volume

Effective Area = 38.5 $IN^2$ Up 1697 $IN^3$ Down 1336 $IN^3$

## Hydraulic Fluid Constants

SQRO = 1. Bulk Modulus ( ß ) = 100,000. Cd = 100.

## Pressures

Supply = 3000. PSI Return = 100. PSI

## Mass

$M = \frac{1}{6}$ (Ring Mass) = 32.37 Slugs

Note; All frictions and hydraulic leakages are assumed to be negligible

TABLE 5-2

The method of determining a frequency response from a non-linear mathematical model is shown in Figure 5-2. The method is based on taking the Fourier series of both the input and output time histories. This method can be interpreted as having the analysis force the model to behave much like a real system when measured by a Fourier analyzer in the laboratory. However the input signal for this case consists of a sum of sine waves at selected frequencies which span a desired range. The Fourier coefficients are then used to determine the appropriate gain and phase of the response. The end result of the analysis is only considered at the frequencies generated by the input signal. (A round off technnique is applied to round off to the nearest milli-Hz) The technique used in the analysis was derived from experimentation with a known linear model describing a transfer function. This was done so that the correct results can be determined and compared with the results of this analysis. Various forms of input signals were tested using this technique. An impulse function was used in several cases. Although the results were close for gain there was an offset in the frequency domain which was affected by how the impulse function was approximated. The phase could not be determined properly using this technique. Random noise was also tested much like a signal analyzer applies the input. This form of input did produce accurate results but required a considerable amount of simulation time and data points to average to a smooth spectrum of frequencies (White Noise). The sum of sine waves was selected because it was a much more controlled input signal and gave accurate results. There were only slight inaccuracies at the low frequencies (first few points) which should not affect control analysis. One drawback with this technique is the limitation of data points generated in the frequency domain. This technique was used previously to validate a non-linear math model describing the M1 gun/turret tracking system. The results gave responses much closer to the measured test data than the linearized model at various operating points.

Figure 5-3 shows the input signal used for this analysis which consist of a sum of sine waves at the frequencies specified. For this particular example the sine waves have a magnitude (or amplitude) of unity. When the Fourier series is evaluated at the frequencies generated the results are a magnitude of unity and angle of 90° as would be expected for this case. The input in the time domain aproaches a function similar to an impulse train as more frequencies are added. One consideration when using this technique is determining what magnitude to use on the sine wave generation. This consideration is similar to determining what operating point to choose when linearizing a model. With some insight and experimentation one can select reasonable magnitudes to use for a particular part of the system. Avoiding saturation levels is the primary concern, however the results are magnitude dependent as would be expected for a non-linear system.

The frequency response analysis will be conducted at selected parts of the system model to determine various plant responses and closed loop responses for each loop configuration. The sine wave generated input will be applied to the model at the input of desired functions while the output is recorded for future use. Once the data file is created from the model, a frequency response analysis can be conducted using a FORTRAN program called Bode. This program is listed in Appendix B and has many applications. When the frequency response represents a plant response the program has the feature of designing compensation to the results. Since compensation is considered a cascade function with the plant response, the total open loop can be determined by simply adding the gain and phase of the functions. The program has the feature of doing this and observing stability margins. The program is menu driven and only takes seconds to vary the compensation to obtain a new open loop response. The following section will describe how this technique was applied to the hydraulic actuator model.

# METHOD FOR DETERMINING A FREQUENCY RESPONSE

**INPUT**

$$Fi(t) = \sum \sin(2\pi ft)$$

SWEEP GENERATOR

Fi(t)

TRANSFER FUNCTION MODEL

**OUTPUT**

Fo(t)

**FOURIER SERIES**

$$ANi(f) = \int_0^T Fi(t)\cos(2\pi ft)\,dt$$

$$BNi(f) = \int_0^T Fi(t)\sin(2\pi ft)\,dt$$

$$ANo(f) = \int_0^T Fo(t)\cos(2\pi ft)$$

$$BNo(f) = \int_0^T Fo(t)\sin(2\pi ft)$$

**MAGNITUDE AND ANGLE**

$$MAGi(f) = \sqrt{ANi(f)^2 + BNi(f)^2}$$

$$MAGo(f) = \sqrt{ANo(f)^2 + BNo(f)^2}$$

$$\Theta i(f) = \mathrm{TAN}^{-1}(\,BNi(f) / ANi(f)\,)$$

$$\Theta o(f) = \mathrm{TAN}^{-1}(\,BNo(f) / ANo(f)\,)$$

## GAIN AND PHASE

MAGi(f)
$\Theta$i(f)

TRANSFER FUNCTION
GAIN(f) & PHASE(f)

MAGo(f)
$\Theta$o(f)

$$\mathrm{PHASE}(f) = \Theta o(f) - \Theta i(f)$$

$$\mathrm{GAIN}(f) = 20\mathrm{Log}(\,MAGo(f) / MAGi(f)\,)$$

This method is evalauted at the frequencies used in the Sweep Generator.

f discrete frequency
t discrete time

FIGURE 5-2

## INPUT SIGNAL USED FOR FREQUENCY RESPONSE

INPUT:

$$\text{INPUT}(t) = \Sigma\ A\ \text{Sin}\ (2\ \pi\ Fn\ t)$$

Where : A desired magnitude
Fn desired frequencies
t simulated time

For our case Fn consist of 42 selected frequencies as follows:

Fn = .2 , .4 ,.6, .8,
1., 1.4, 1.6, 2.0, 2.4, 3.0, 3.4, 4.0, 4.4, 5.0, 5.4, 6.0, 6.4,
7.0, 7.4, 8.0, 8.4, 9.0, 10.0,
14.0, 20.0, 24.0, 30.0, 34.0, 40.0, 44.0, 50.0, 54.0, 60.0
64.0, 70.0, 75.0, 80.0 ,85.0, 90.0, 95.0, 99.0 Hz

Which gives the following time history:

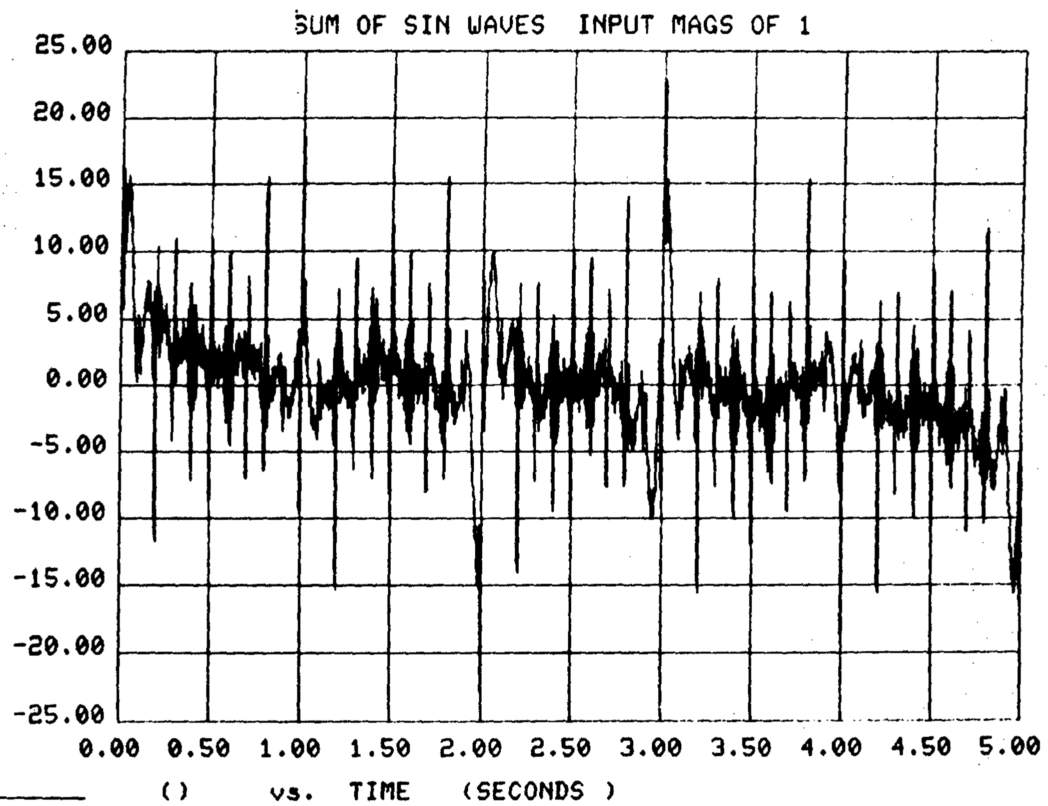
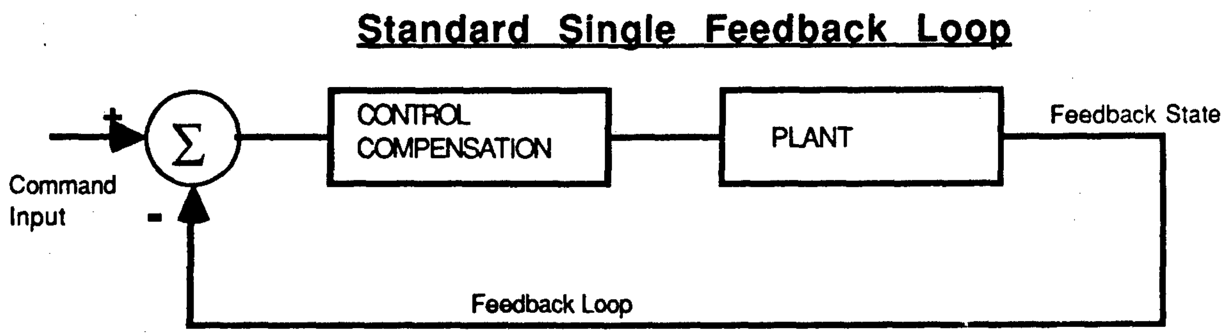



FIGURE 5-3

## 5.3 CONTROL DESIGN ANALYSIS

Shown in Figure 5-4 is a block diagram of the actuator system. The system comprises three feedback loops for control. The states containing feedback are position, rate and pressure. Some notes received show the inner loop to be force rather than pressure. This should only result in a difference in gain in the inner loop. When designing control compensation with classical control theory most fundamental text books describe the following simplified system:




Where the compensation is the only portion of the system which is subject to change. The plant is considered that portion of the system which is left unchanged. The design consist of deriving compensation which produces the end result or performance. For this analysis, the multi-loop system will be reduced to three systems with a single feedback, such as the system shown above. This procedure will be conducted one step at a time until the entire system is established. Figure 5-5 shows the procedure in more detail for each step. The frequency response mentioned earlier will be used as the tool to evaluate a plant response, closed loop response and design compensation by observing the open loop response.

### 5.3.1 PRESSURE LOOP RESPONSE

Shown in Figure 5-6 is the inner loop block diagram which illustrates in more detail the inner loop configuration including the valve dynamics. The blocks after the compensation are considered the plant for this case. The plant response is shown in Figure 5-7 for gain and phase. The valley at .4 Hz may be a numerical problem and will not have any influence on stability. The peak at 10 Hz represents the hydraulic resonance due to compression of the fluid. Figure 5-8 shows the pressure compensation frequency response which was derived by experimentation by observing the open loop response which resulted in Fiqure 9 for the compensation described. The goal was to establish the highest gain cross frequency with still maintaining adequate stability margins (See Figure 5-9). The end result is the pressure loop response shown in Figure 5-10. The closed loop response indicates a bandwidth greater than 62 Hz and a very quick step response. This gives an indication to how quick the system will build up pressure to the actuator for a desired 1500 PSI command. The step response was obtained by running the computer model in closed loop form and compensation design intact with a step command as pressure command. This verifies the design which was derived in the frequency domain.

## ACTUATOR SYSTEM BLOCK DIAGRAM

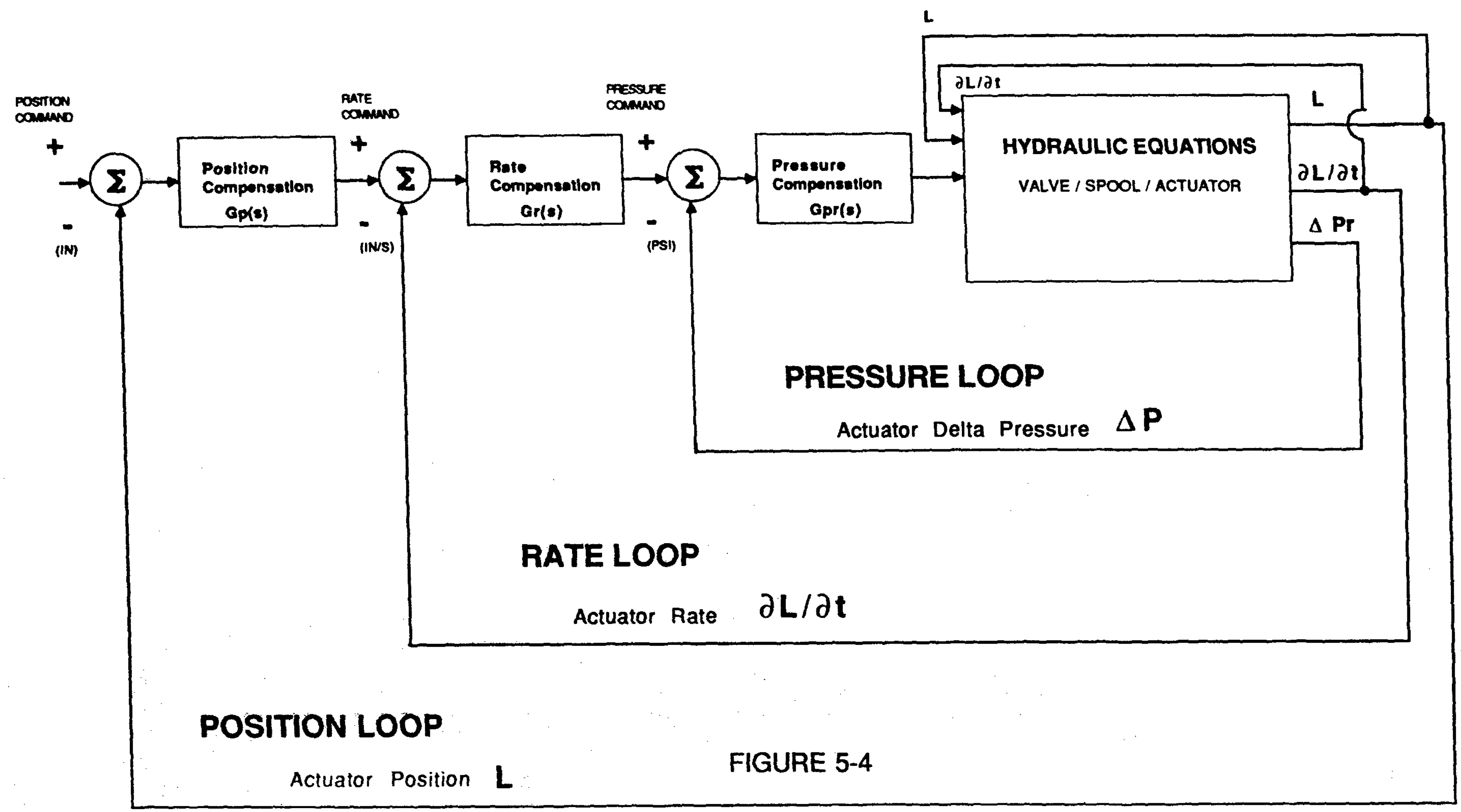



FIGURE 5-4

# CONTROL DESIGN PROCEDURE

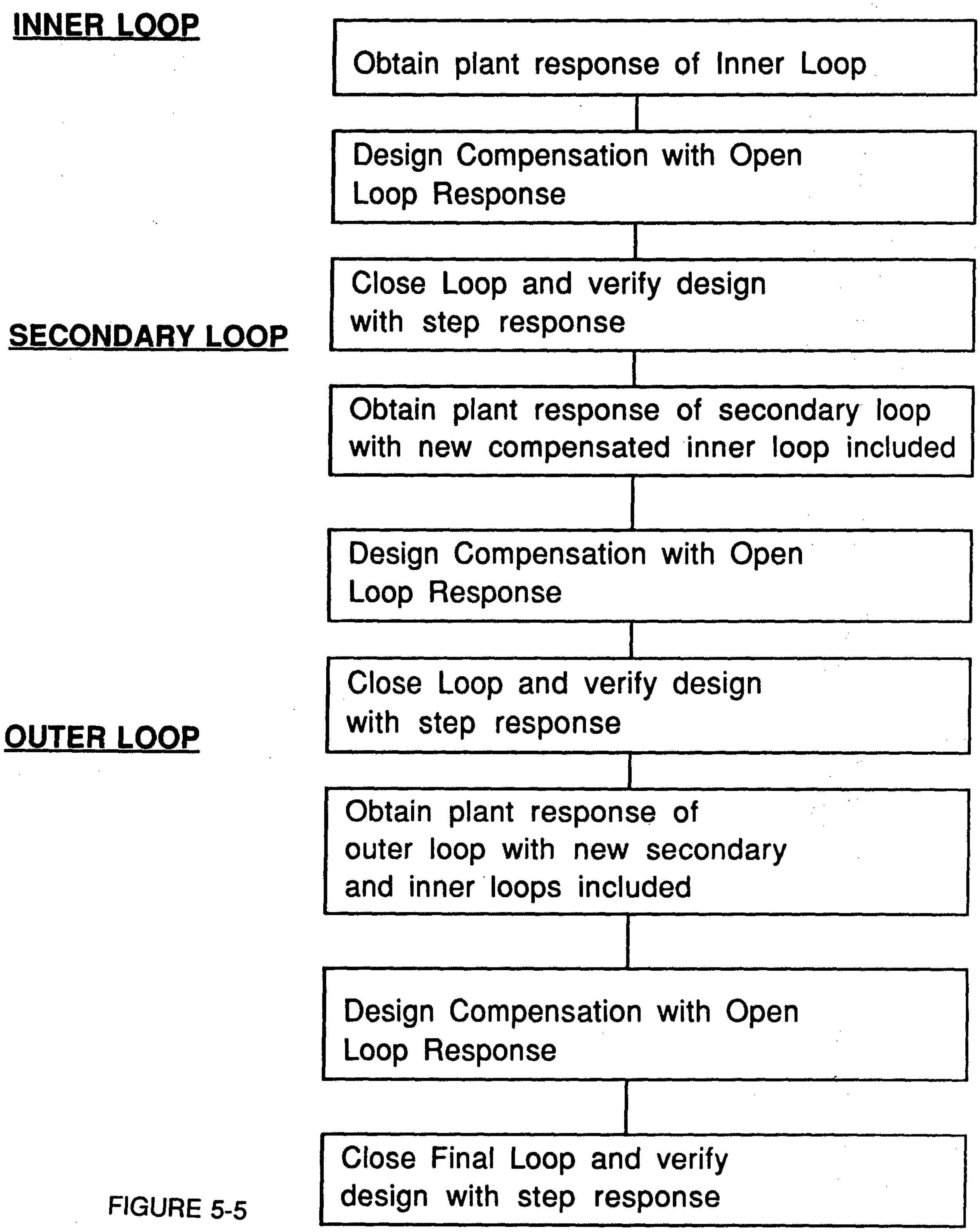
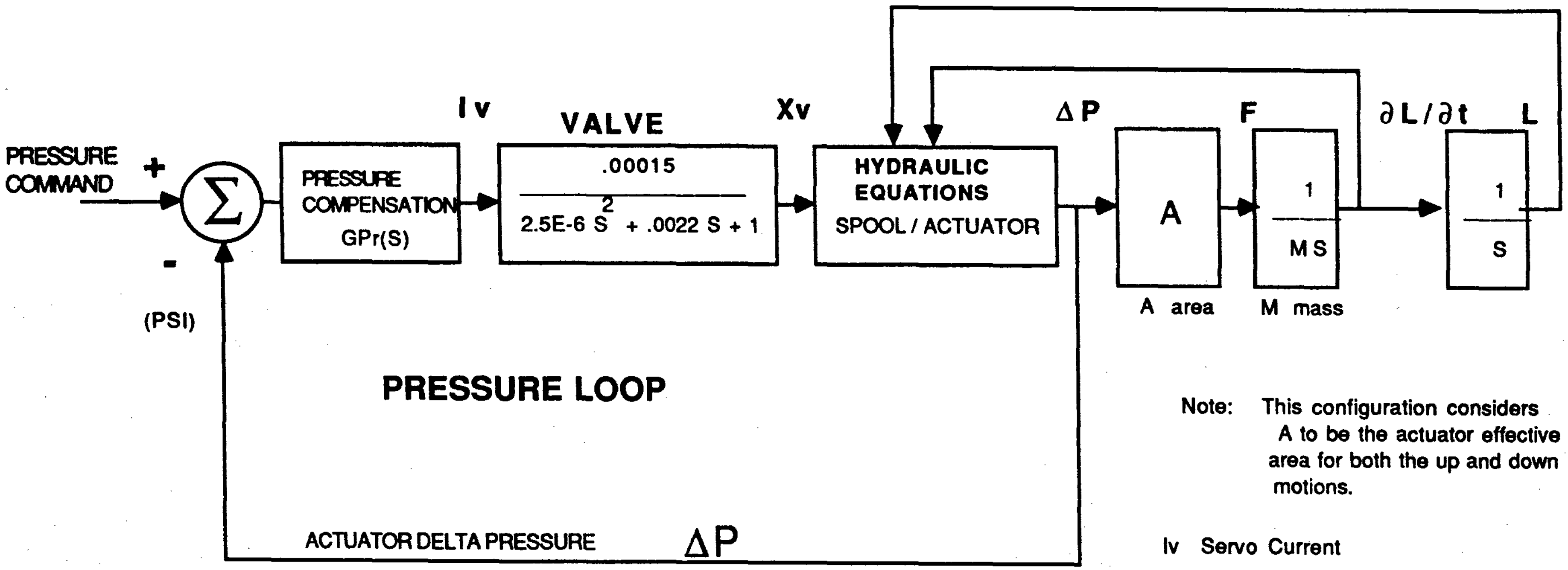



FIGURE 5-5

# PRESSURE LOOP BLOCK DIAGRAM

(INNER LOOP)




Note: This configuration considers A to be the actuator effective area for both the up and down motions.

Iv Servo Current

Xv Spool Position

ΔP Delta Actuator Pressure

F Actuator Force

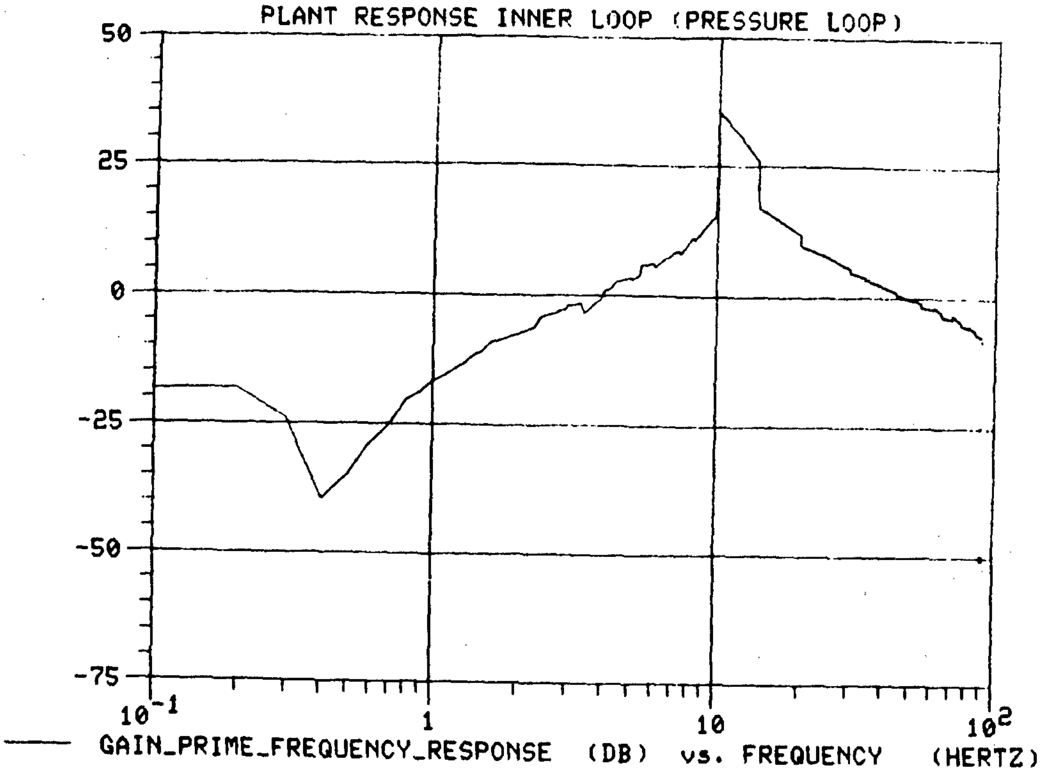
∂L/∂t Actuator Rate

L Actuator Position

FIGURE 5-6

# Plant Frequency Response of Pressure Loop

## Gain




## Phase

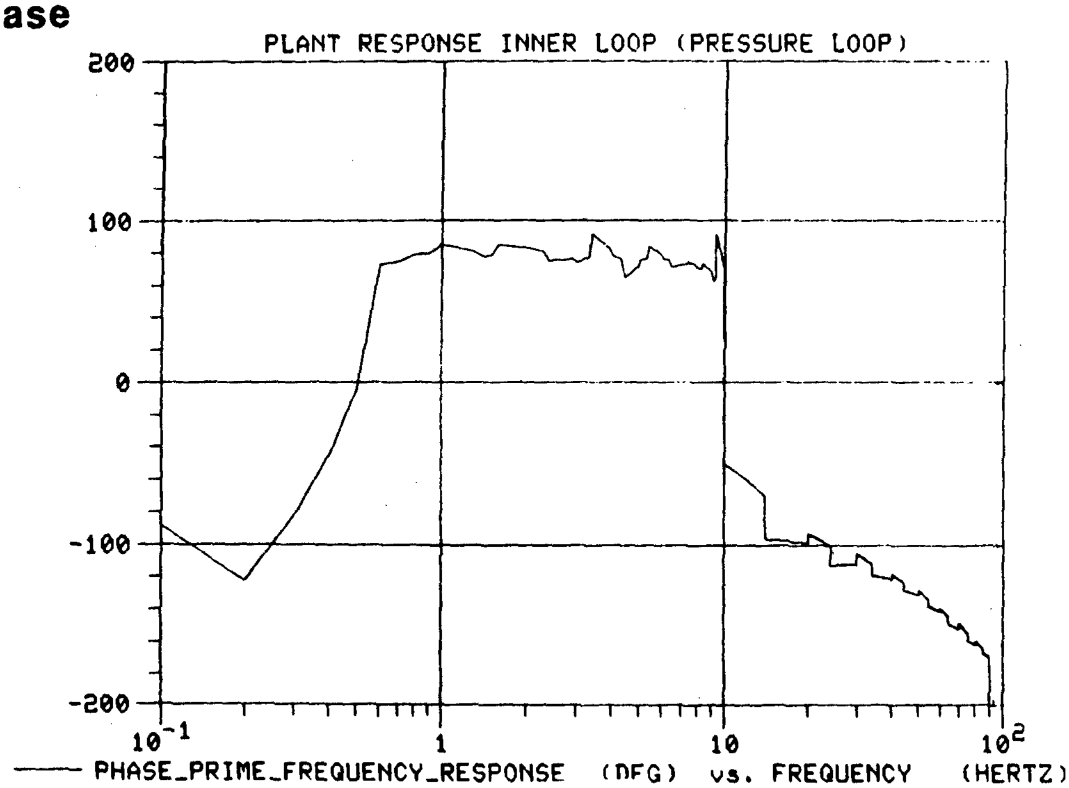
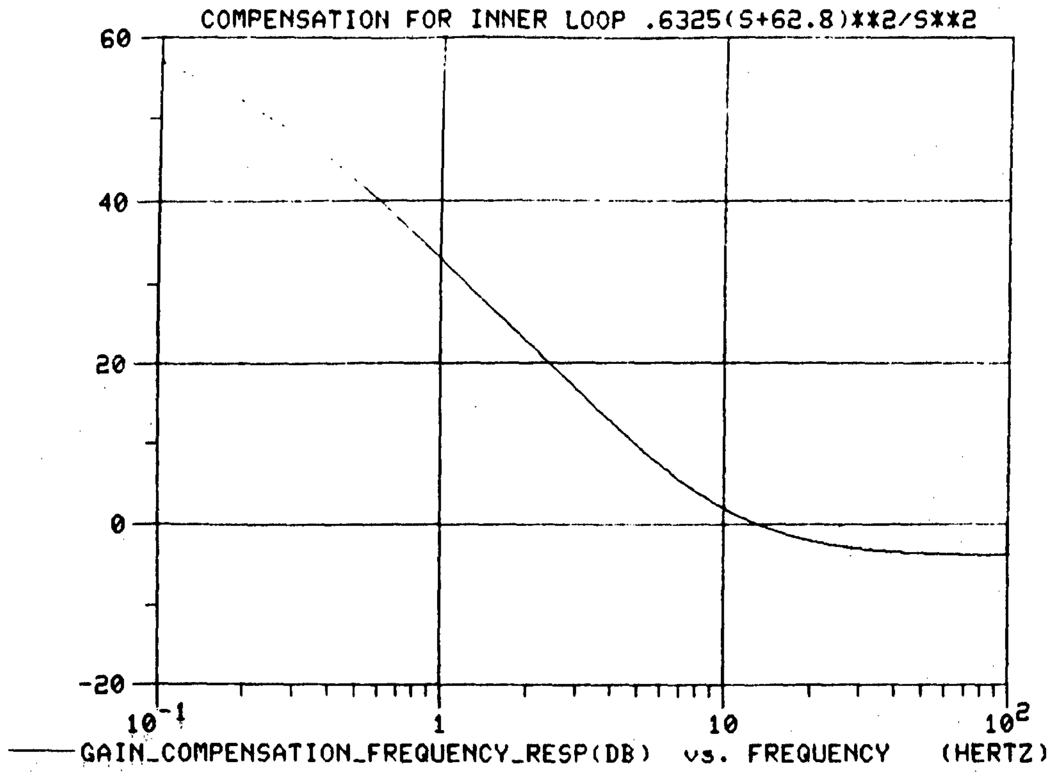



FIGURE 5-7

## Compensation Frequency Response of Pressure Loop

### Gain




### Phase

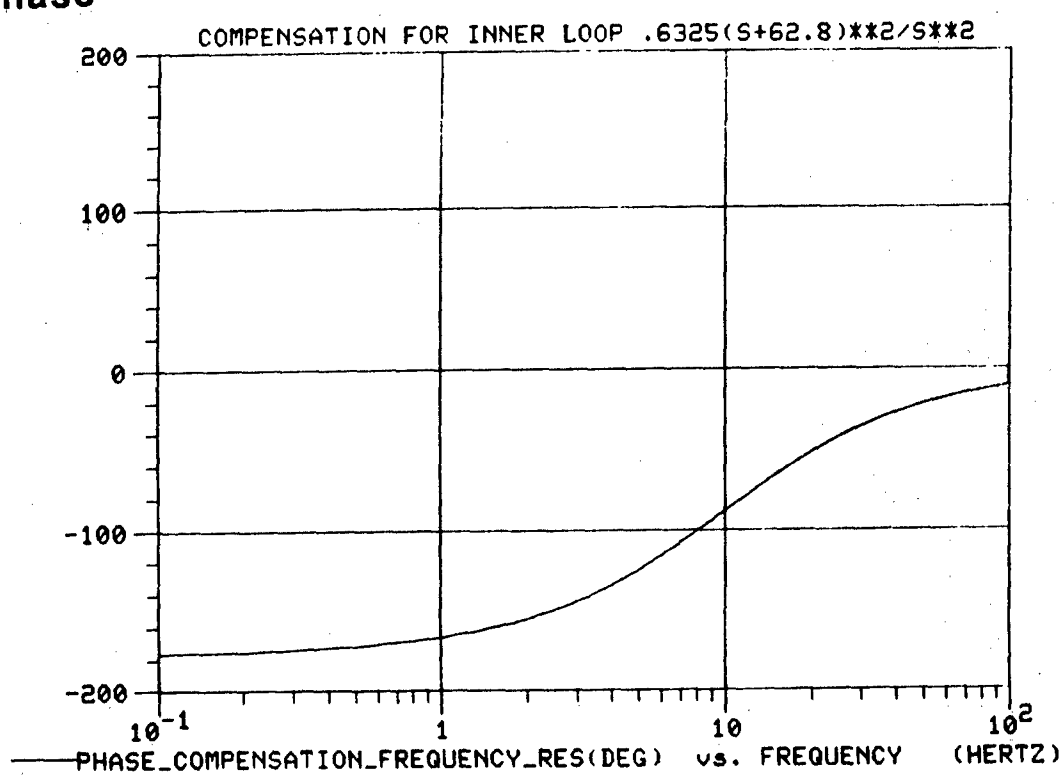


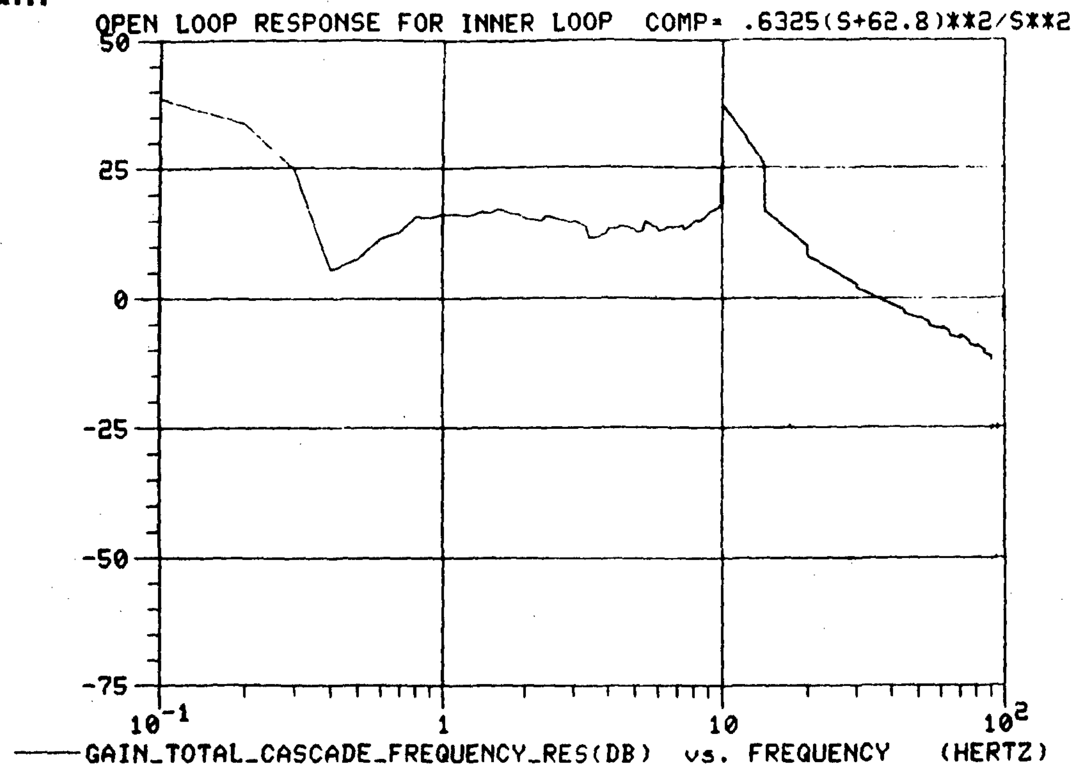

FIGURE 5-8

# Open Loop Frequency Response of Pressure Loop

Gain Margin = 10.2 dB

Gain Cross 35.3 Hz

## Gain




Phase Margin = 28.9°

Phase -180° Cross 85.1 Hz

## Phase

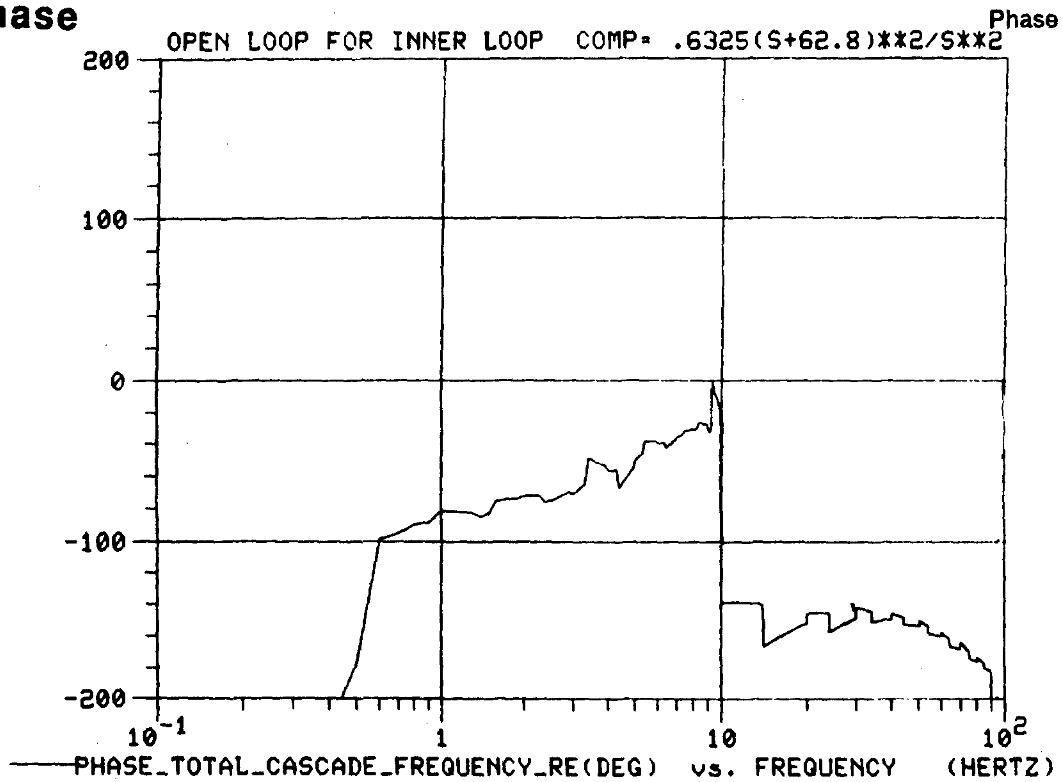
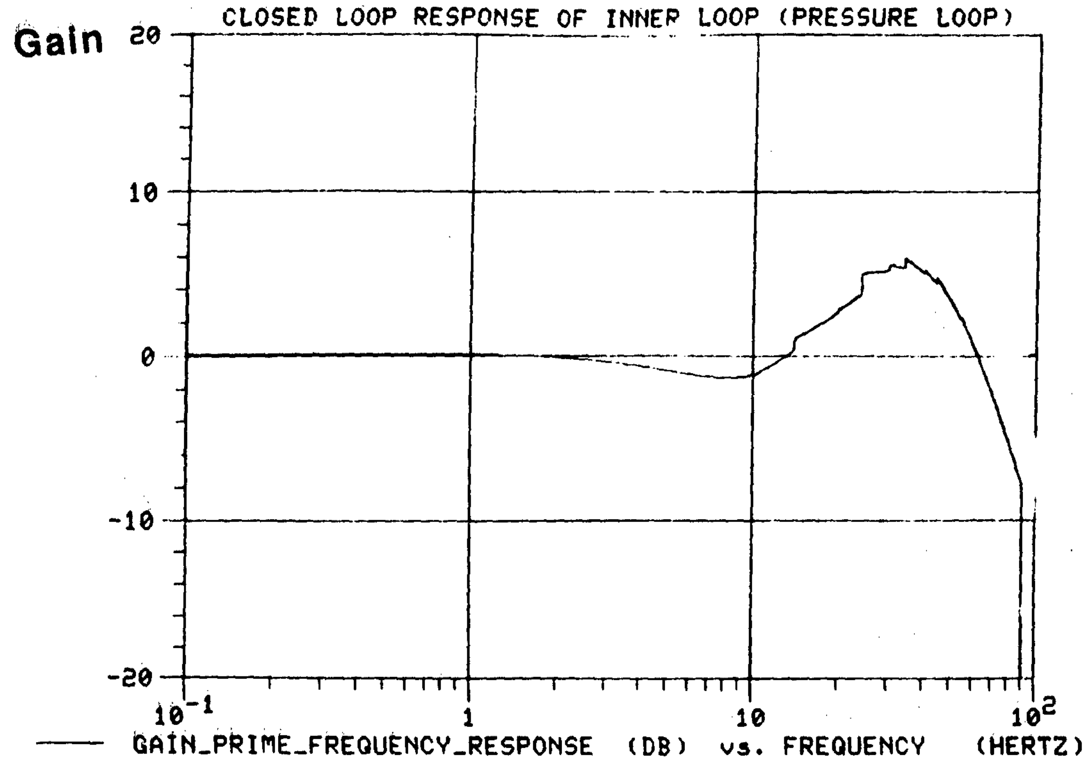



FIGURE 5-9

## Closed Loop Response of Pressure Loop

Gain Cross 62. Hz




## Step Response

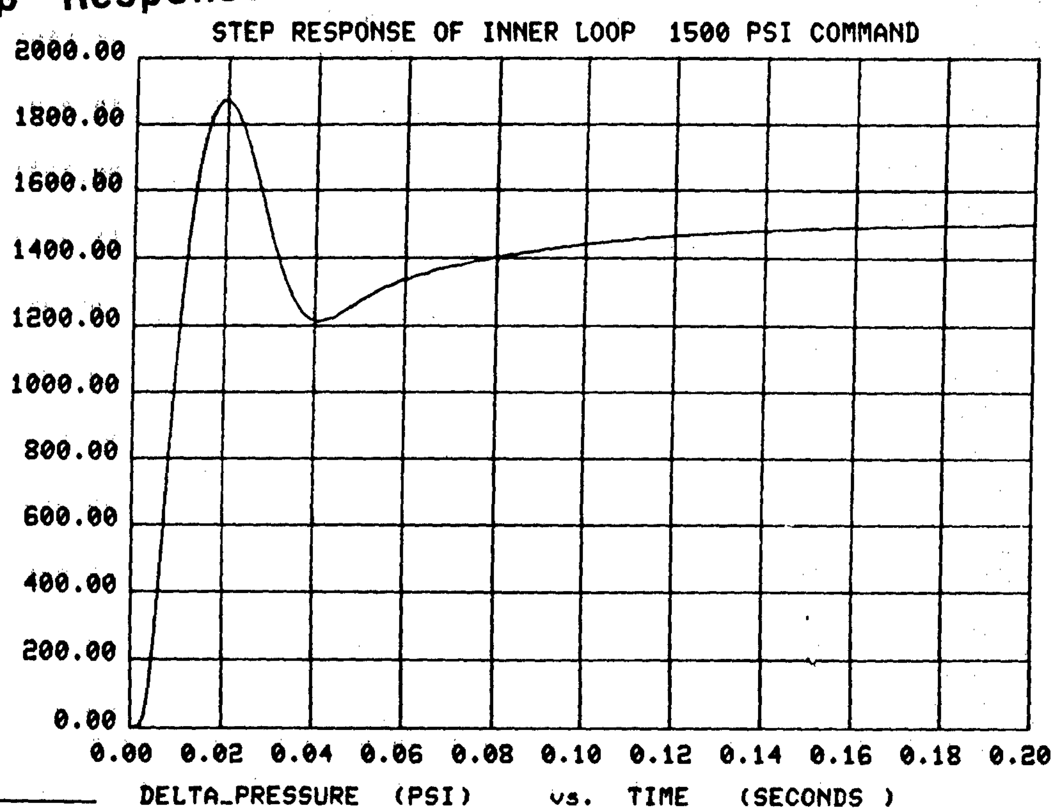



FIGURE 5-10

The compensation for the inner loop was determined to be a second order transfer function. A first order transfer function resulted in a steady state error. It was decided to increase the type number of the system (Number of pure integrators). The result is using two PI (Proportional + Integral) controls in cascade instead of a single one.

### 5.3.2 RATE LOOP RESPONSE

The same procedure is now used for the rate stage of the system model which is illustrated in Figure 5-11. The plant is now considered to be the entire new inner (pressure) loop which includes the compensation which was just created. Figure 5-12 shows the frequency plant response for the rate loop The compensation was a single PI control shown in Figure 5-13. The resulting open loop response is shown in Figure 5-14. The results are shown in Figure 5-15 with the closed loop response and the step response. The gain cross is over 38 Hz for the closed loop response. The step response indicates some ringing but settles within .12 seconds. Perhaps the stablility margins could have been improved for this stage. However, at this time the primary concern was to establish an adequate response for the overall system which is in terms of a position command response.

### 5.3.3 POSITION LOOP RESPONSE

With the new pressure and rate loops having compensation design, the final stage can be evaluated, completing the system. Figure 5-16 shows the position loop configuration. The plant now includes the new pressure and rate loops, which has a response shown in Figure 5-17. The compensation is not shown because it simply has a gain of 31.6 to establish good stability margins. The total open loop response is shown in Figure 5-18. The step response is well damped and has a settling time of about .2 seconds as shown in figure 5-18. The bandwidth is 10.1 Hz as shown in closed loop frequency response shown in Figure 5-19. There is always a compromise between stability margins and bandwidth performance. The bandwidth can be easily raised for this system if desired. A simple increase in compensation gain will result in a quicker response but produce more overshoot and ringing. The general consideration for this application is to have a quick response with minimal overshoot.

## 5.4 RESULTS

Shown in Table 5-3 are the results of the compensation design. These results are considered adequate at this time. It is illustrated that there is a correlation between the stability margins and step response characteristics. Control compensation can be designed with this technique and may prove to be of value if the model is accurate or is modified for improving its accuracy. Some of the frequency responses derived here for control design are not always possible to measure on the actual system. This stresses the importance of establishing a design analytically before doing the fine tuning or "tweeking" of the controls in the laboratory. Analytical design gives insight into which direction to go with various gains of the controller.

# RATE LOOP BLOCK DIAGRAM

(SECONDARY LOOP)

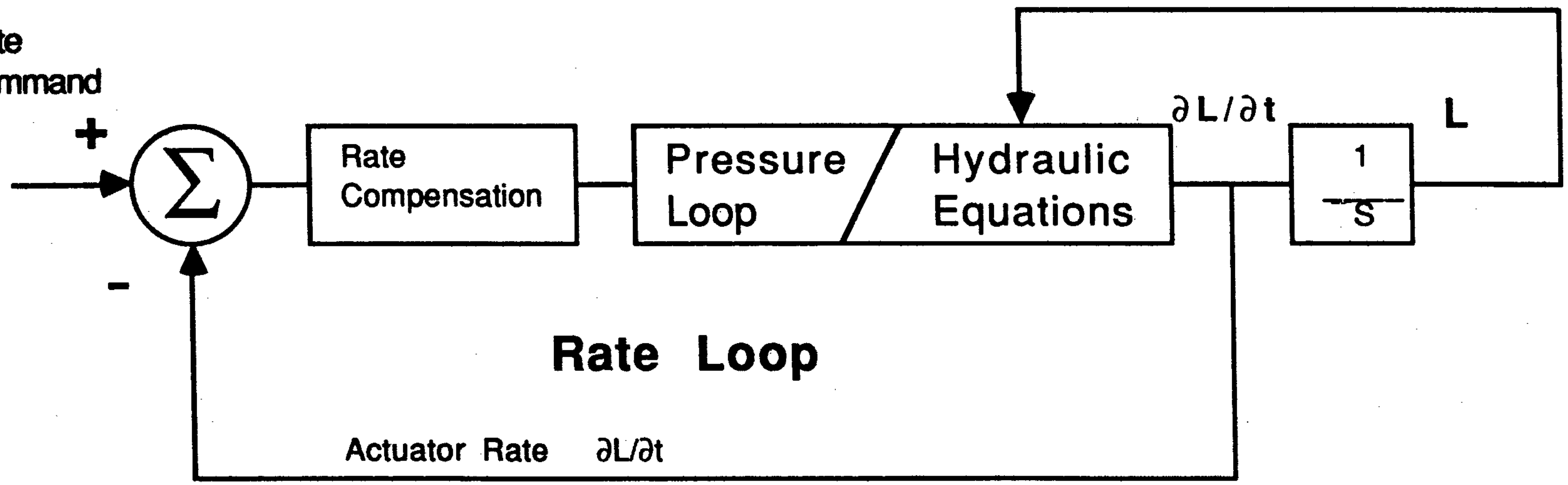
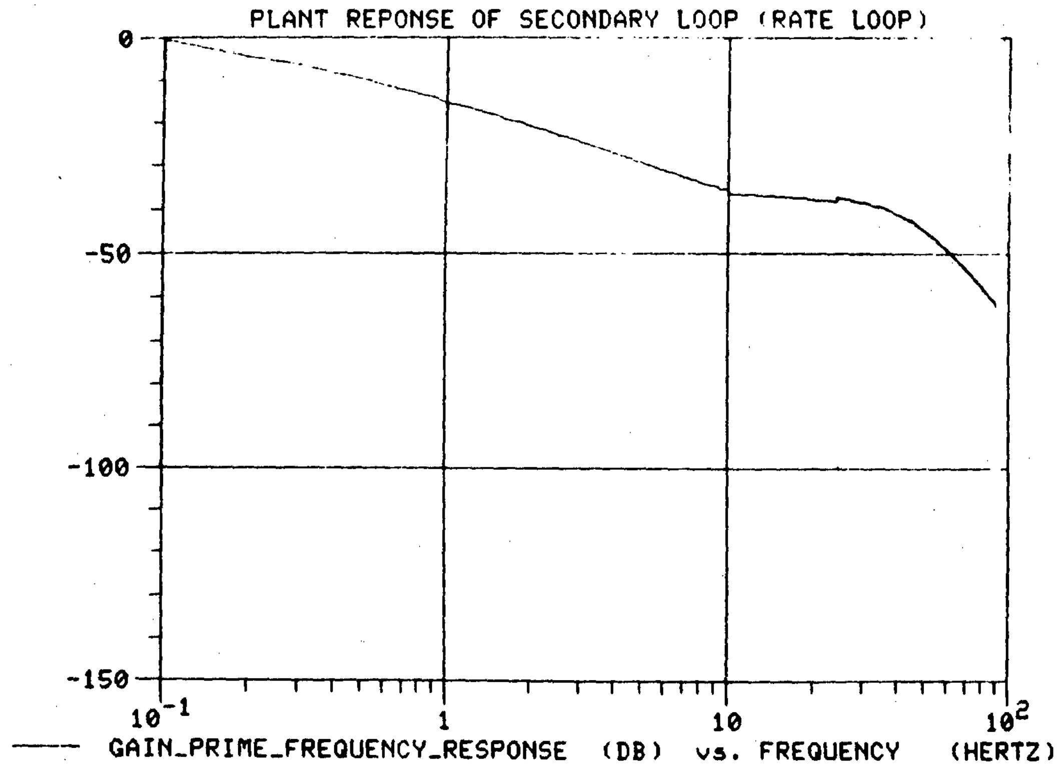



FIGURE 5-11

# Plant Frequency Response of Rate Loop

## Gain




## Phase

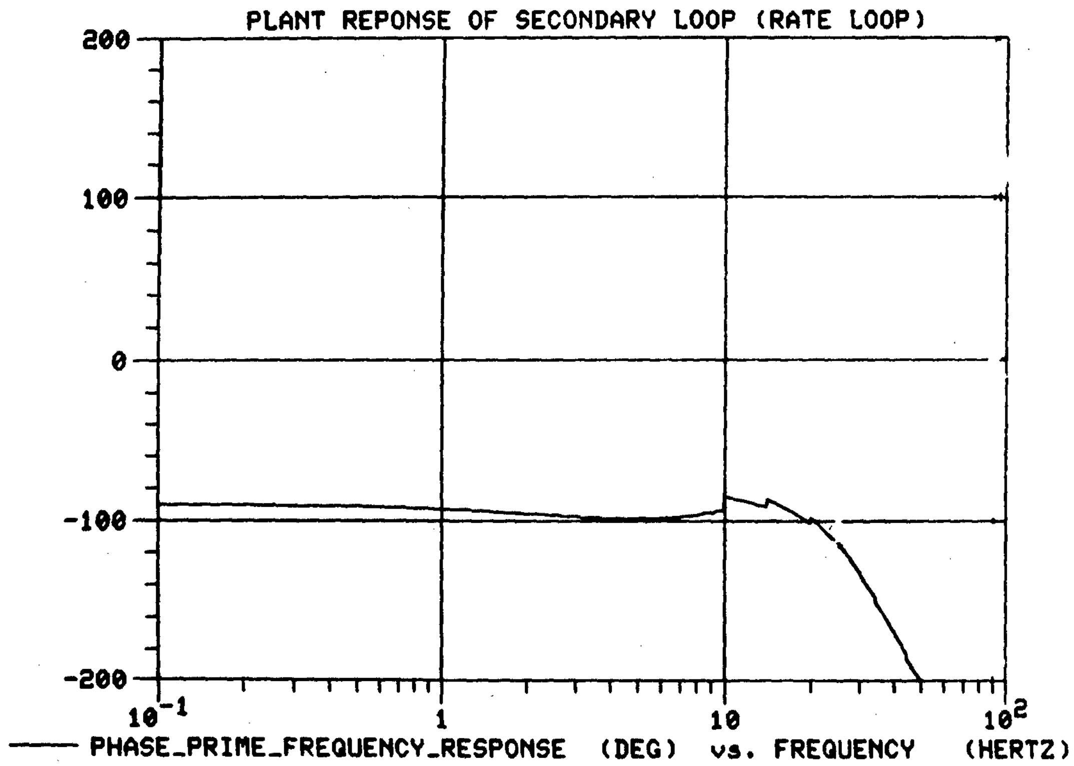
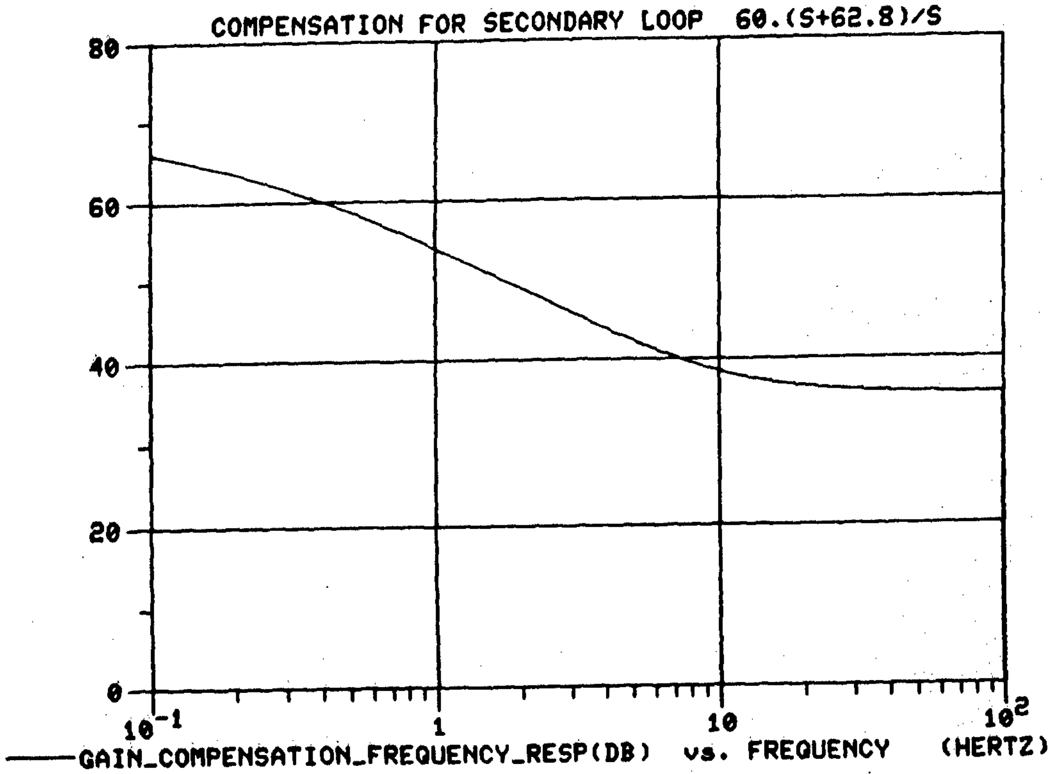



FIGURE 5-12

## Compensation Frequency Response of Rate Loop

### Gain




### Phase

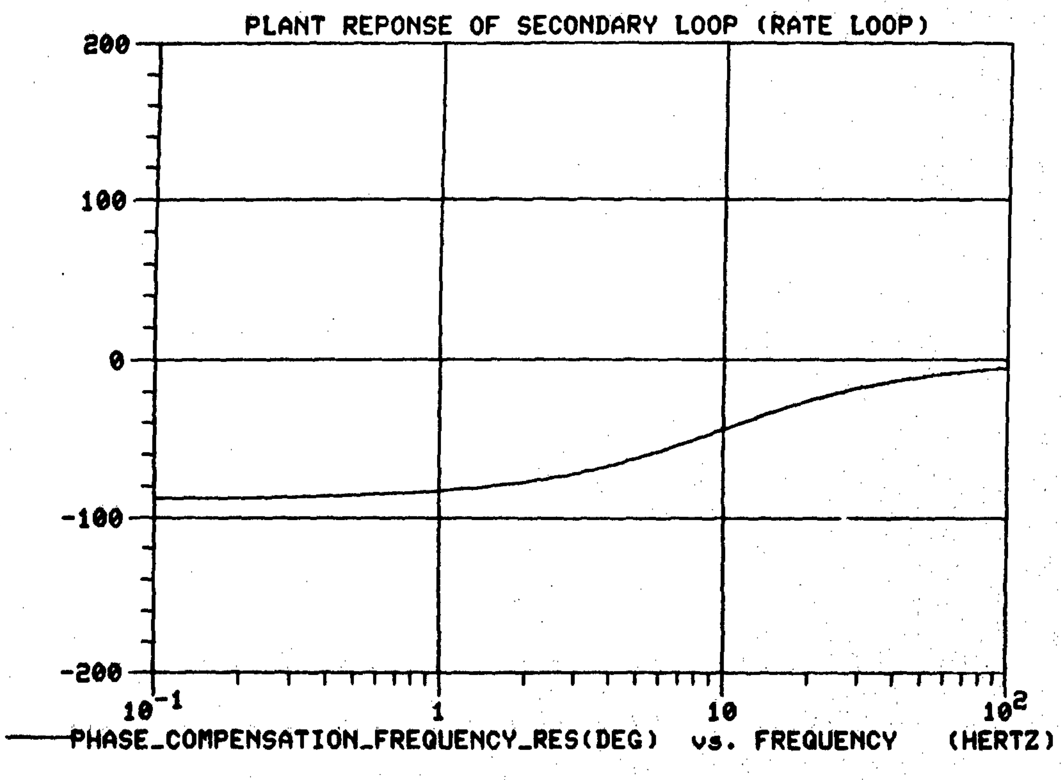
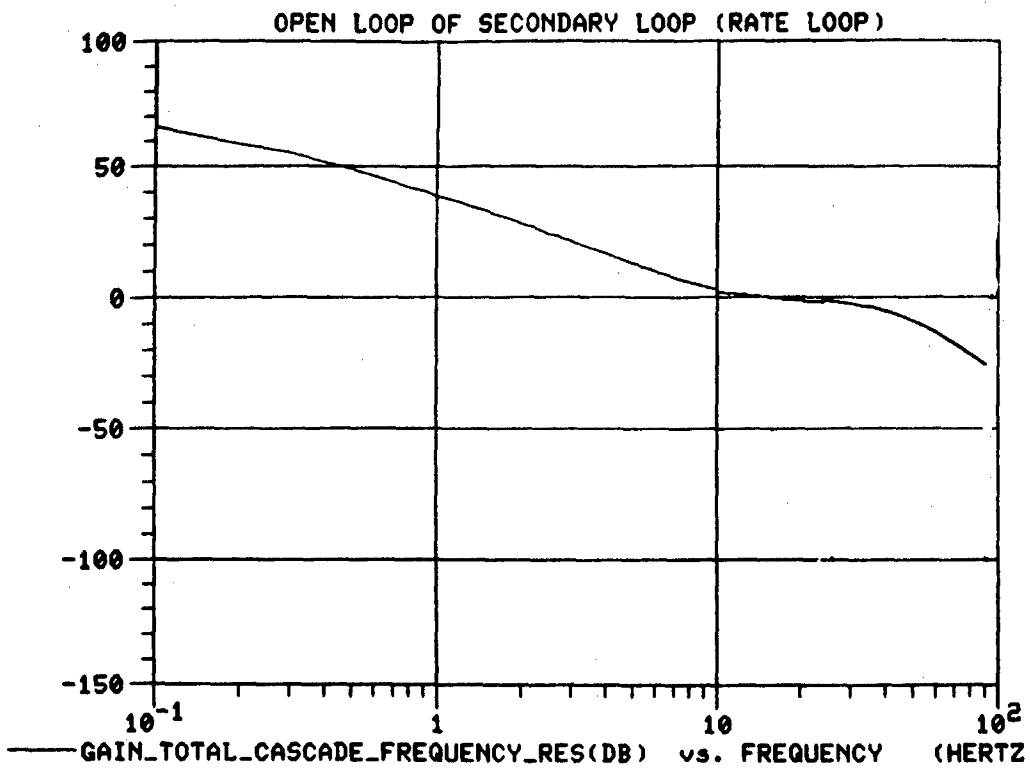



FIGURE 5-13

# Open Loop Frequency Response of Rate Loop

Gain Margin = 5. dB
Gain Cross 14.7 Hz

## Gain




Phase Margin = 58°
Phase -180° Cross 38.9 Hz

## Phase

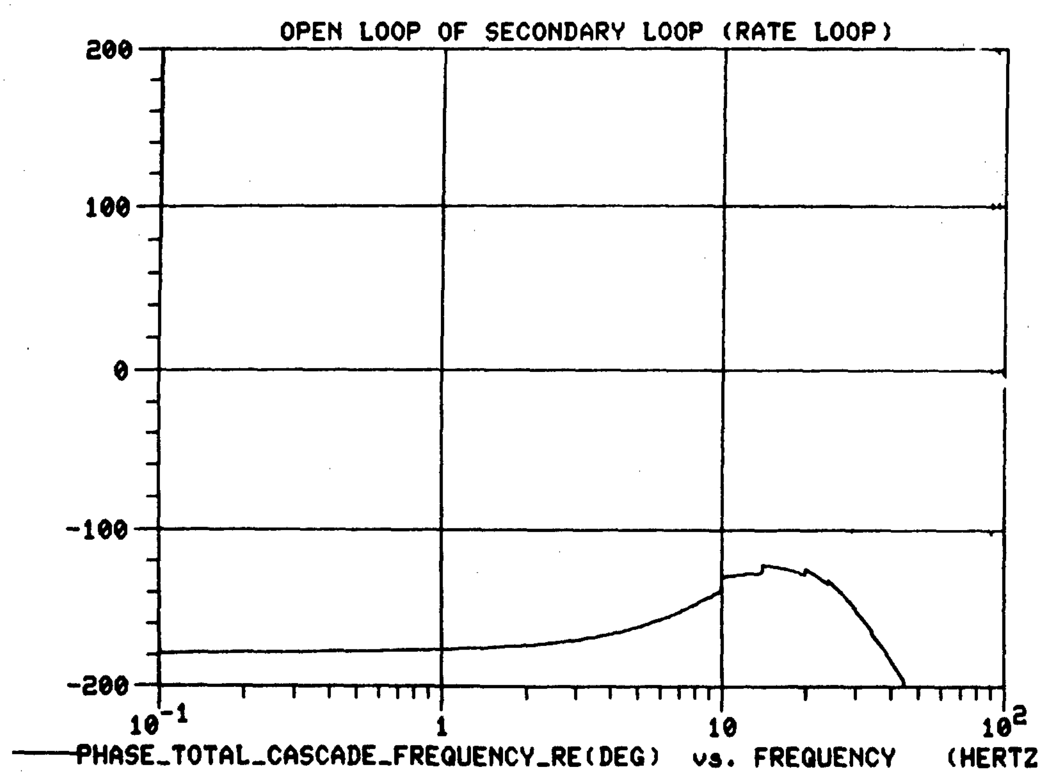
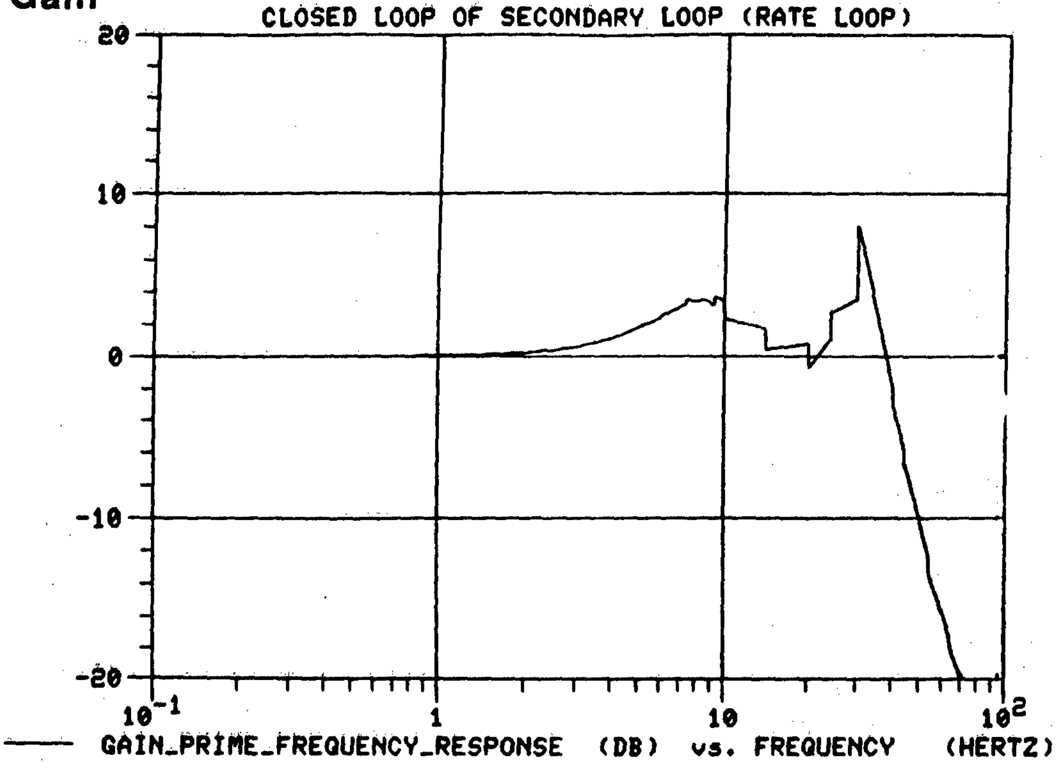



FIGURE 5-14

## Closed Loop Response of Rate Loop

Gain Cross 38.Hz

### Gain




### Step Response

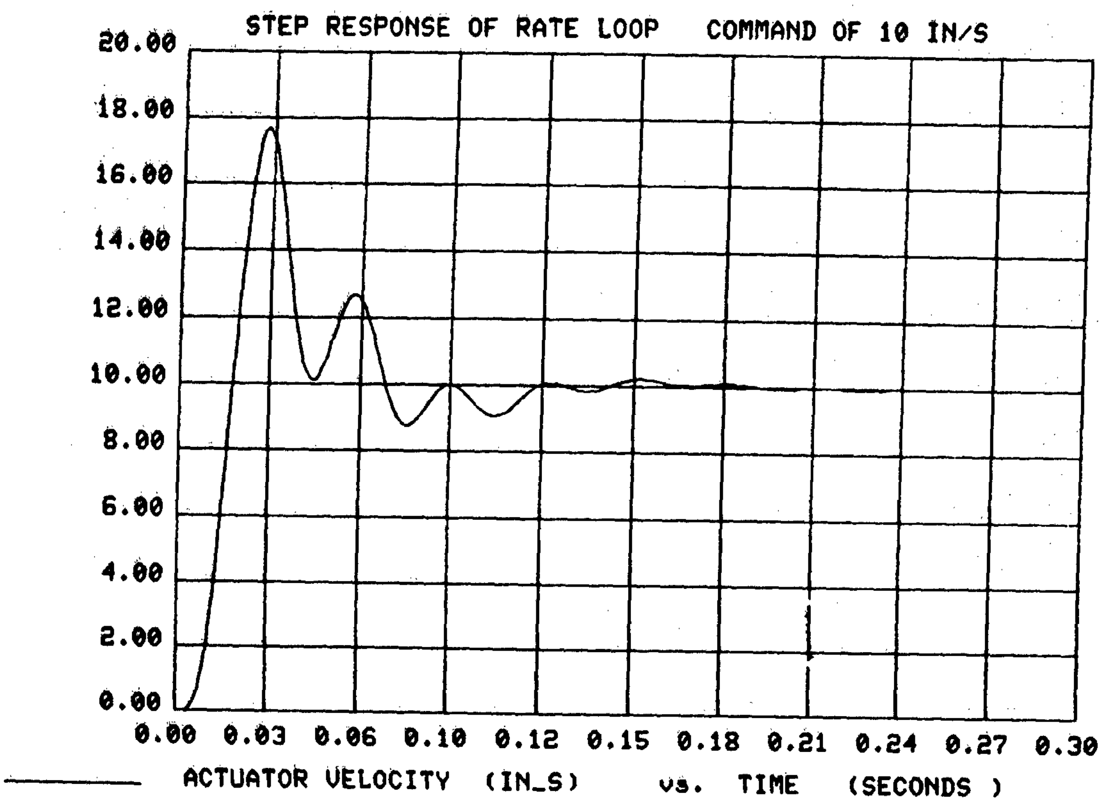



FIGURE 5-15

## Position Loop Block Diagram

(Outer Loop)

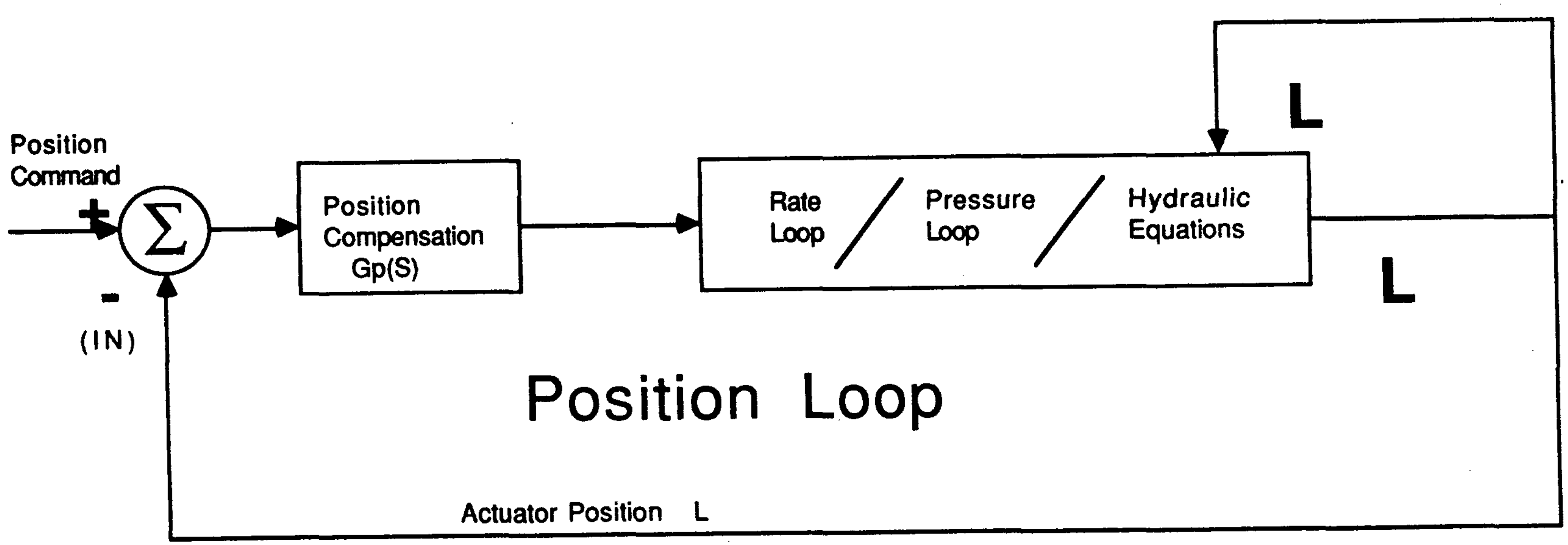
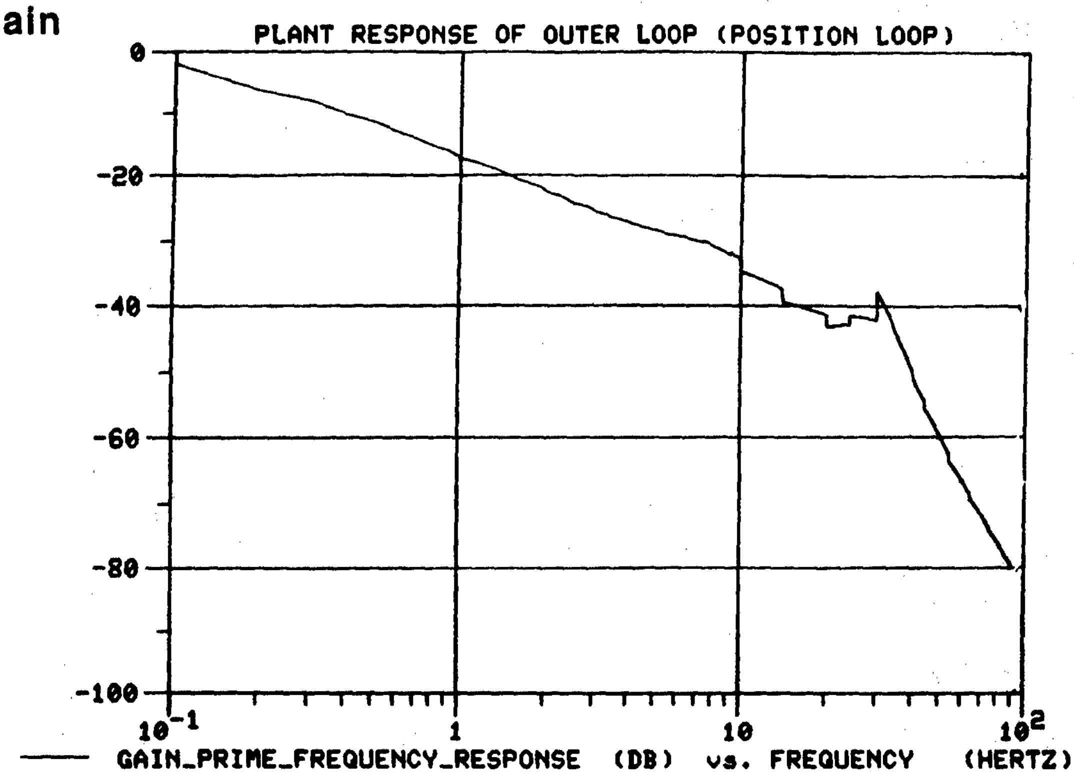



FIGURE 5-16

## Plant Frequency Response of Position Loop

Gain




Phase

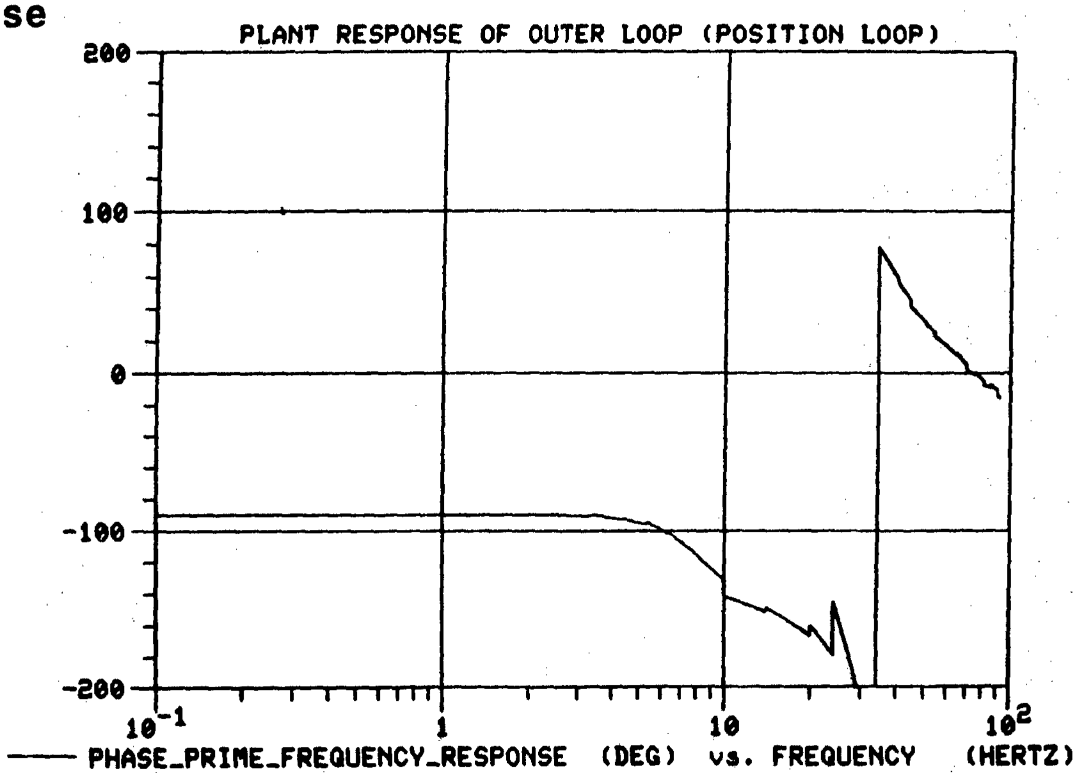
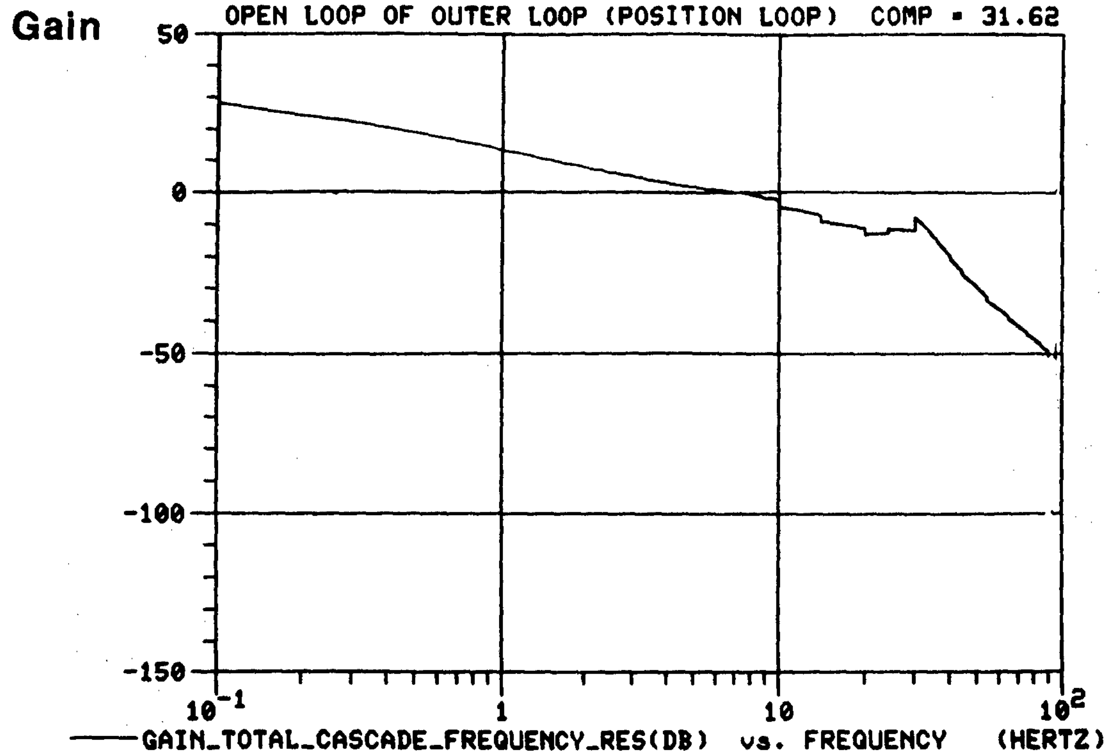



FIGURE 5-17

# Open Loop Frequency Response of Position Loop

Gain Margin = 11.7 dB

Gain Cross 7.1Hz




Phase Margin = 75°

Phase -180° Cross 27.5 Hz

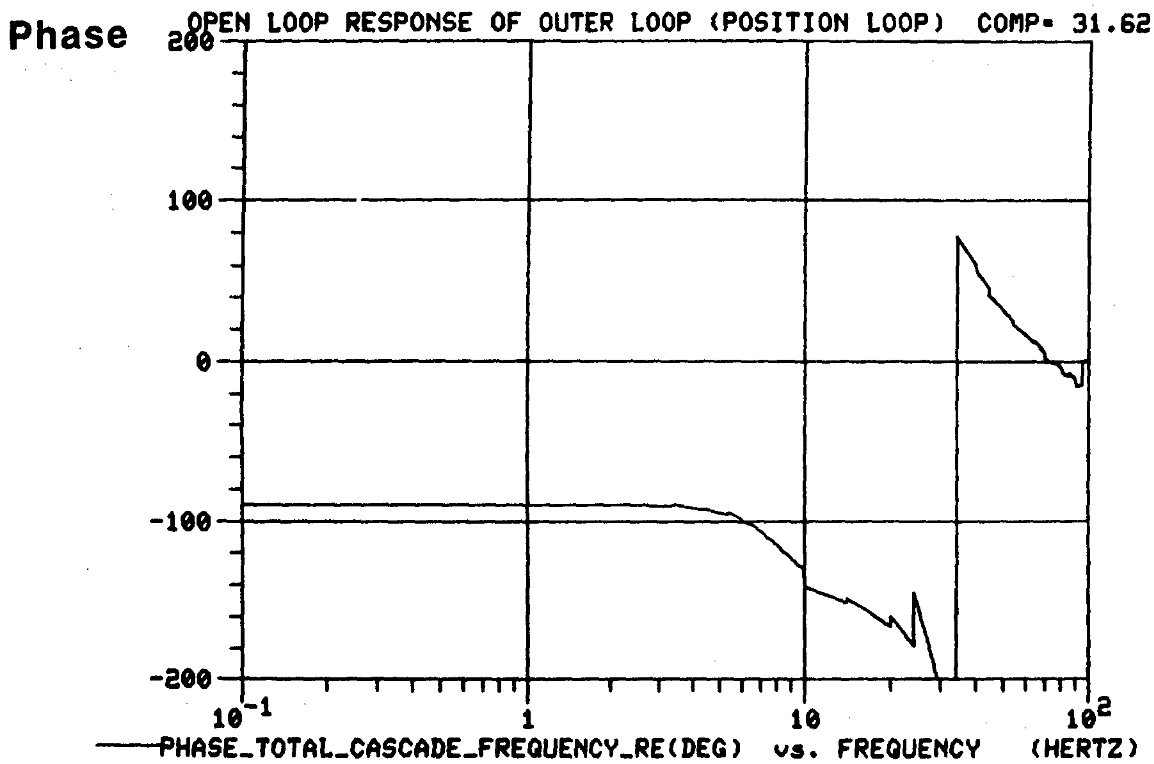
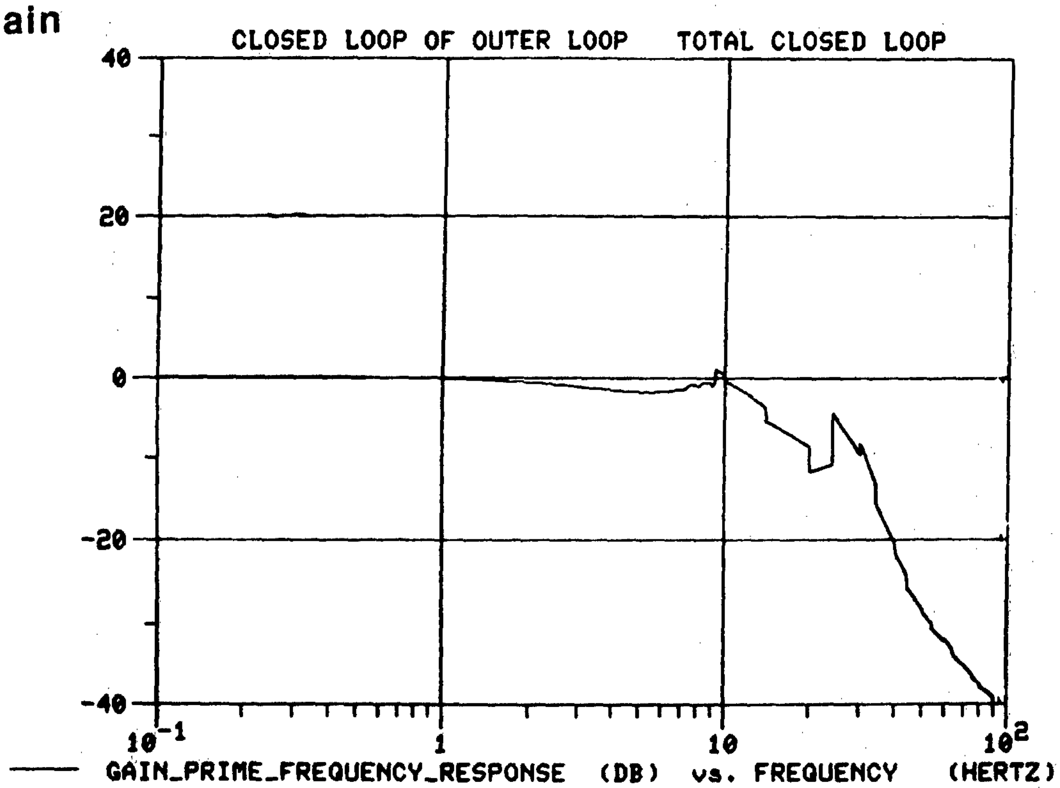



FIGURE 5-18

# Closed Loop Response of Position Loop

Gain Cross 10.1 Hz

## Gain




## Step Response

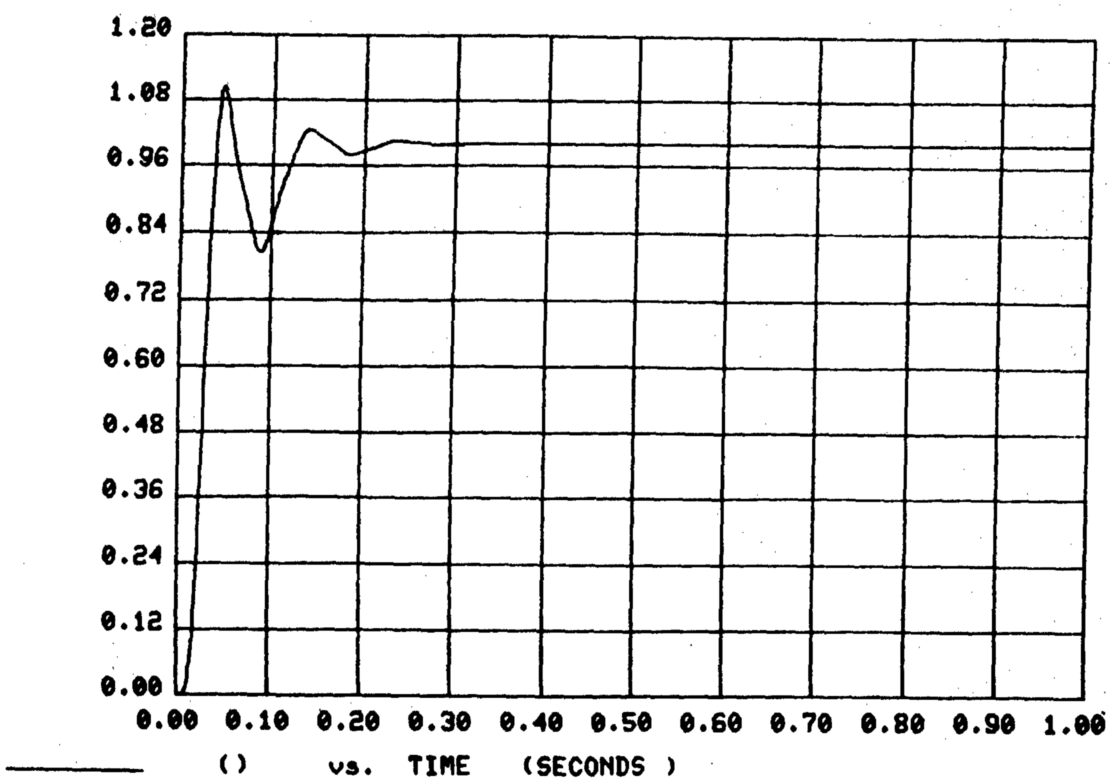



FIGURE 5-19

# Results Of Controller Design

| | Compensation | Stability Phase | Margins Gain | Closed Loop Cross (0 dB) | Step Response Command | Settling Time | Overshoot |
|---|---|---|---|---|---|---|---|
| **Pressure Loop** | $Gpr(S) = \frac{.633(S + 62.8)^2}{S^2}$ | 28.9 ° | 10.2 dB | 62 Hz. | 1500 PSI | .1 S | 26 % |
| **Rate Loop** | $Gr(S) = \frac{60.(S + 62.8)}{S}$ | 58.0 ° | 5.0 dB | 38 Hz | 10 IN/S | .12 S | 75 % |
| **Position Loop** (Total Loop) | $Gp(S) = 31.6$ | 75.0 ° | 11.7 dB | 10.1 Hz | 1. IN | .2 S | 10 % |

TABLE 5-3

Shown in Appendix C are the results of a simulated step response. This Appendix includes various simulated states of the system such as pressures, flows, entrained volumes, spool displacement etc. A step response is obtained by applying a position step command to the system. A step response is used in the analysis to verify control design and give an indication to the performance of the system. This type of command signal may not always be practical to directly apply to real actuator systems due to harshness. This is especially true for a position command signal. As can be seen by the plots that the states are driven to large values the first few milli-seconds of the simulation. These values point to additional limits which should be incorporated in the model. The servo current has a spike value of 2000 milliamps (2 amps) which is an excessive value.

Investigations are being made on filtering techniques which will filter command signals before they are applied to the system. Previous laboratory testing consisted of detrend and filtering processes which modify command signals as described in some detail in Reference 5. In addition low pass filters are used in the laboratory which essentially smooth command signals. This would round off command signals representing step functions (Filter high frequency content). A command signal which has been filtered would reduce some of the enormous overshoots revealed by these simulations.

Appendix D includes the simulated actuator response to various levels of step command. The response changes as the level of command is varied, illustrating the non-linear characteristics of the system. The control design procedure introduced in this report could be conducted at various signal levels to produce a compensation design for a given signal level. This form of adaptive control could be incorporated in software to interactively select the appropriate control compensation for a given signal level. With this design a control design could be made which gives good results for all operating regions of the system.

Appendix E shows the actuator responses to a variation of mass. These results show that as the actuator is loaded with mass the transient response is drastically changed. In fact the system becomes unstable as the mass is increased beyond 60 slugs. This is due to the influence mass has on the plant response characteristics of the system which in turn has a direct impact on the stability margins. To some extent, a change in gain of the rate loop should compensate (adjust) to variation in mass. However, this does not completely improve the system response as bandwidth performance is expected to decrease. These characteristics stess the importance of adaptive control for the TMBS where variations in inertia are expected to reflect on each of the actuator's stability and performance. Additional concern is the coupling effects that each actuator will induce on each other. An analytical investigation will cover these problems in the near future.

## LIST OF REFERENCES

1. Helinski, A. L. , "Deriving an Empirical Model of an Electrohydraulic Actuator System from Frequency Response Data", RDE Center Technical Report No. 13368, U. S. Army Tank-Automotive Command, Warren, MI (June, 1988)

2. Kaminski, A. P., "A Mathematical Representation of the M60A1 Azimuth and Elevation Control", General Dynamics (Chrysler Corporation- Defense Division) System Analysis Technical Report (November 1971)

3. CADS Inc., "DADS Rev. 5.0 Supplement Manual", DADS Control/Hydraulic Element Theoretical Manual. Computer Aided Kinematics and Dynamics of Mechanical Systems. 1988

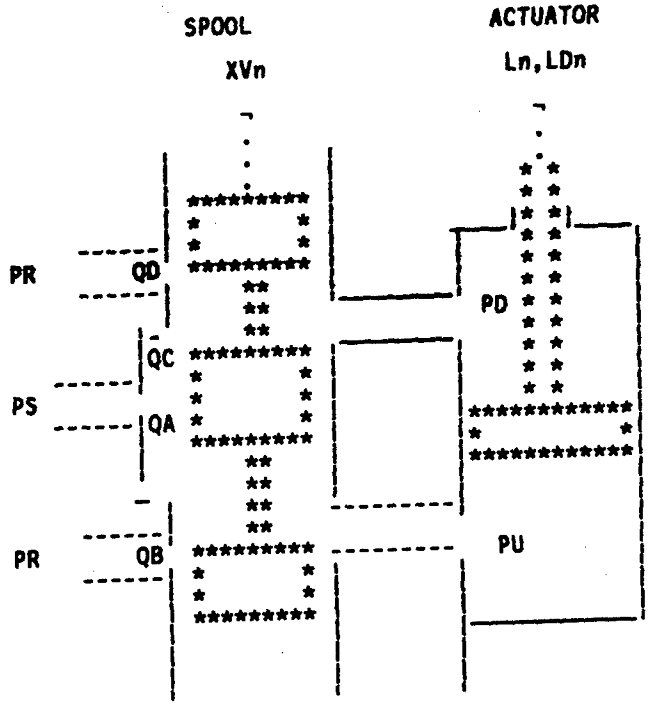
4. Various unpublished notes from Contraves Goertz Corporation related to Turret Motion Base Simulator (TMBS) hydraulic system. Includes an AD10 code and DADS model listings. (1987)

5. Helinski, A. L. , "Simulation Test of the MK19 MOD3 Grenade Machine Gun Support Kit", RDE Center Technical Report No. 13297, U. S. Army Tank-Automotive Command, Warren, MI (October 1987)

# APPENDIX A
# LIST OF HYDRAULIC ACTUATOR COMPUTER MODEL

```
  PROGRAM  SA_CLOSED_LOOP
" "
" SINGLE UNCOUPLED ACTUATOR SYSTEM MODEL  for TMBS                  "
" "
   cinterval cint=0.001
   ARRAY GFREQ(50)
   REAL DOUT(9000)
   INTEGER INDEX,NTABLE   $"USED FOR SAMPLING INDEX"
" The following arrays "
"        are used to describe the transfer function coefficient"
   ARRAY SERVN,SERVD(3)
" SERVO TRANSFER FUNCTION COEFFICIENTS"
   CONSTANT SERVN = 1.5E-4
   CONSTANT SERVD = 2.533E-6 , .002228 , 1.
"  INITIAL ENTRAINED VOLUME and RING MASS "
   CONSTANT V10=1697. , V20=1336. , RMASS=194.26
" MECHANICAL PARAMETERS FOR VALVE"
"          BULK - OIL BULK MODULAS"
   CONSTANT CD=100. , SQRO=1. , BULK = 100000.
"          VALVE SPOOL CIRCUMFERENCE"
   CONSTANT W1=3.787 , W2=3.787
"          UP - LOW CYLINDER AREA"
   CONSTANT AREA1=38.5 , AREA2=38.5
"          SUPPLY & RETURN PRESSURE"
   CONSTANT PS=3000. , PR=100.
" "
INITIAL
   INDEX=0
   CALL READFREQ(GFREQ,GLEVEL,NTABLE=)
END $" OF INITIAL "
"*********************************************************************"
DERIVATIVE
"  *********  LEG COMMAND SIGNAL ******************"
      "        LE1=    LEG ERROR"
      "        LC1=    LEG COMMAND"
      "        L1=     LEG DISPLACEMENT"
" "
"  GENERATE SIGNAL FOR FREQUENCY ANALYSIS   "
"  LC1   POSITION COMMAND                   "
" "
PROCEDURAL(LC1=GFREQ,GLEVEL,NTABLE,T)
      CALL GENERATE(LC1,GFREQ,GLEVEL,NTABLE,T)
END$"  OF PRCEDURAL-GENERATE"
" "
     LE1 = LC1 - L1
     " "
"  *********  POSITION LOOP COMPENSATION *********"
     "        RC1=  COMPENSATED LEG ERROR SIGNAL"
     RC1 = KP*(LE1+OMEGP*INTEG(LE1,0.))
     " "
"  ********* VELOCITY LOOP COMPENSATION **********"
     "        LDE1= LEG VELOCITY COMMAND"
     "        LD1=  LEG VELOCITY SIGNAL"
     "        PRC1= PRESSURE COMMAND ???????"
     LDE1 = RC1 - LD1
*
     KT = 60.
     OMEGT = 62.8
     PRC1 = KT*(LDE1+OMEGT*INTEG(LDE1,0.))
" "
"  ********* PRESSURE LOOP COMPENSATION **********"
```

```
"        PE1=  PRESSURE ERROR       "
"        IV1  SERVO VALVE CURRENT"
 KDP = .633
 OMEGDP = 62.8
 PE1 = PRC1 - DELTP1
 IVA1 = KDP*(PE1+OMEGDP*INTEG(PE1,0.))
 IV1  = 1. *(IVA1 + OMEGDP*INTEG(IVA1,0.))
" "
"  ********** SERVO VALVE DYNAMICS *****************"
"         XV1=  SERVO VALVE POSITION               "
 XV1 = TRAN(0,2,SERVN,SERVD,IV1)*********************** "
"*************************************************************"
"********************* HYDRAULIC SECTION *****************"
"*************************************************************"
```




```
n:   Index for Actuator

PRESSURES:     PSn   Supply Pressure
(PSI)          PRn   Return Pressure
               PUn   Actuator Pressure Up
               PLn   Actuator Pressure Down

FLOWS:         QAn   Flow IN from supply { Up  }
(In3/S)        QBn   Flow OUT to return  { Up  }
               QCn   Flow IN from supply {Down }
               QDn   Flow OUT to return  {Down }

INPUT:         XVn   SPOOL POSITION from neutral
(In)
```

```
"                                                                   "
"          ACTUATOR:     Ln    POSITION (IN)                        "
"                        LDn   RATE     (IN)                        "
"                                                                   "
"                                                                   "
"                                                                   "
" ********** CONDITION THE SPOOL POSITION XV *********"
" ********** FOR UPPER AND LOWER CONSIDERATION *********"
"******************************************************"
"                                                     "
"                                                     "
"            XVD1  for spool down                     "
"            XVU1  for spool up                       "
" "
    XVD1= RSW(XV1 .LT. 0.,-XV1,0.)$" SPOOL DOWN"
    XVU1= RSW(XV1 .GT. 0.,XV1,0.)$" SPOOL UP  "
"                                                     "
"     FLOW COEFICIENT  Cd                             "
"             Q = C*X*SQRT(DELTA P)                   "
"     where   C=Cd*W1*SQRT(2/DENS)      W1=PI*D       "
" "
" ********* FLOW FROM PRESSURE DROPS  ****************"
 QA1 = CD*SQRO*W1*XVU1*SQRT(ABS(PS-PU1))*SIGN(1.0,PS-PU1)
 QB1 = CD*SQRO*W1*XVD1*SQRT(ABS(PU1-PR))*SIGN(1.0,PU1-PR)
 QC1 = CD*SQRO*W1*XVD1*SQRT(ABS(PS-PD1))*SIGN(1.0,PS-PD1)
 QD1 = CD*SQRO*W1*XVU1*SQRT(ABS(PD1-PR))*SIGN(1.0,PD1-PR)
" "
" ********* CYLINDER VOLUME VOLUn & VOLDn **************"
    VOLU1 = V10  +    L1*AREA1
    VOLD1 = V20  -    L1*AREA2
" ********* DERIVATIVE OF PRESSURE PDOTUn & PDOTDn******"
    PDOTU1 = (BULK/VOLU1)*(QA1 - QB1 - AREA1*LD1)
    PDOTD1 = (BULK/VOLD1)*(QC1 - QD1 + AREA2*LD1)
" "
" ********  INTEGRATE FOR PRESSURE PU1 & PD1 ***********"
    PU1 = INTEG(PDOTU1,0.)
    PD1 = INTEG(PDOTD1,0.)
" "
" "
" ********* DELTA PRESSURE ACROSS PISTON **************"
    DELTP1 = PU1 - PD1
" "
" ******** ACTUATOR FORCE Fn  *************************"
   F1=AREA1*PU1 - AREA2*PD1 - FRICT $" MUST LOGIC THE FRICTION"
" "
" **** SIMPLIFY FOR NOW ACTUATOR VELOCITY AND POSITION ********"
"   ACTUATOR FORCE Qn"
" "
   MASS=RMASS/6.    $" Assume a single unconstained mass for now"
   LD1 = (1./MASS)*INTEG(F1,0.) $"actuator velocity inches"
   L1  = INTEG(LD1,0.)
" "
END $"OF DERIVATIVE"
"******************************************************************"
"*** DISCRETIZE THE OUTPUT INTO ARRAY FOR WRITING OUTPUT *******"
"******************************************************************"
DISCRETE SAMPLE
     INTERVAL DTSMP=.0012207
     STEP=.0012207
     INDEX=INDEX+1
     DOUT(INDEX2)=L1
```

```
END $"OF DISCRETE SAMP 2"
" *******************************************************"
DERIVATIVE
     termt(INDEX2 .GE. 4098)
END $"OF DERIVATIVE"
" "
TERMINAL
     CALL WRITEERD(=STEP,INDEX2,DOUT)
END $"OF TERMINAL"
END $"OF PROGRAM
      SUBROUTINE READFREQ(GFREQ,GLEVEL,NTABLE)
      REAL GFREQ(50)
      CHARACTER*30 FILEN
*
      WRITE(5,100)
100   FORMAT(///////////////////////////////,
     +      ' Enter The File with the frequency table?',/,
     +      ' Example:  freqs.dat')
      READ(5,140)FILEN
140   FORMAT(A30)
      OPEN(10,FILE=FILEN,FORM='FORMATTED',SHARED,
     + STATUS='OLD',ERR=210)
      READ(10,400)GLEVEL
400   FORMAT(/,G10.4)
      NTABLE=1
800   READ(10,600)GFREQ(NTABLE)
600   FORMAT(G10.4)
      IF(GFREQ(NTABLE) .LT. 0.)GOTO 300
      NTABLE=NTABLE+1
      GOTO 800
210   WRITE(5,170)
170   FORMAT(' ERROR OPENING FILE')
300   CLOSE(10)
      RETURN
      END
      SUBROUTINE GENERATE(SINPUT,GFREQ,GLEVEL,NTABLE,T)
*
*     This subroutine creates the sweep wave (Sum of sine waves)
*     for creating the input signal to a frequency response
*     analysis to determine transfer function characteristics.
*
      REAL GFREQ(50)
      SINPUT=0.
      PI=3.141592654
      DO 100 II=1,NTABLE
         SINPUT=SINPUT + GLEVEL*SIN(2*PI*T*GFREQ(II))
100   CONTINUE
      RETURN
      END
      SUBROUTINE WRITEERD(STEP,NSAMP,OUTPUT)
*
      CHARACTER*80 ERD_TITLE,LONG_TITLE,DUMMY80
      CHARACTER*64 ERD_FILE,HDR_FILE,ERD_FILE_O,HDR_FILE_O
      CHARACTER*32 LONG_NAME(16),DUMMY32
      CHARACTER*12 DUMMY
      CHARACTER*8 SHORT_NAME(16),UNIT_NAME(16),XUNIT,DUMMY8
      CHARACTER*4 ERD,HDR
      CHARACTER*1 COMMA,REPLY
```

```
      CHARACTER*2 IOPERATE(20)
      DIMENSION SMAX(18),SMIN(18)
      REAL*4 SCALE(16),OFFSET(16),DATA(16,30000)
      REAL RMS(16),SMEAN(16),OUTPUT(7000)
      INTEGER*4 START_SAMP_ELIM,END_SAMP_ELIM
      INTEGER*2 ERD_UNIT,HDR_UNIT,IDATA(16)
      LOGICAL*4 TIME
      LOGICAL*1 NEWCHAN,RECHAN
      DATA ERD_UNIT,HDR_UNIT/10,11/
      ERD = '.ERD'
      HDR = '.HDR'
************************************************************
*
      WRITE(5,1881)
1881  FORMAT(///,' ENTER how many channels are output')
      READ(5,*)NCHAN
*
      DO 1998 J=1,NCHAN
       WRITE(5,1888)J
1888   FORMAT(///,' ENTER the LONG NAME for channel ',I2)
       READ(5,1889)LONG_NAME(J)
1889   FORMAT(A32)
       WRITE(5,1992)J
1992   FORMAT(//,' ENTER the SHORT NAME for channel ',I2)
       READ(5,1920)SHORT_NAME(J)
1920   FORMAT(A8)
       WRITE(5,1993)J
1993   FORMAT(//,' ENTER the UNIT NAME for channel ',I2)
       READ(5,1920)UNIT_NAME(J)
*
       OFFSET(J)=0.
       SCALE(J)=1.
*
1998  CONTINUE
*
      DO 1766 ISMP=1,NSAMP
        DATA(1,ISMP)=OUTPUT(ISMP)
1766  CONTINUE
*
      WRITE(5,201)
201   FORMAT(//,' Indicate how new data file is to be stored.',/,
     +'      0 = 2 byte integer (binary)',/,
     +'      1 = 4 byte floating point (binary)',/,
     +'      2 = 8 byte floating point (binary)',/,
     +'      3 = 8 byte complex (binary)',/,
     +'      4 = 16 byte complex (binary)',/,
     +'      5 = formatted floating point.  The format is (Nchannels)E13.
     +6',/,'$Enter selection (0-5):(1 CHOSEN MOST COMMONLY) ')
      READ (5,*) KEYNUM
*
* do not let the user choose complex numbers
*
      IF (KEYNUM .EQ. 3 .OR. KEYNUM .EQ. 4) THEN
         TYPE*,' '
         TYPE*,'Choose another format besides complex numbers.'
       ELSE IF(KEYNUM .LT. 0 .OR. KEYNUM .GT. 5) THEN
         TYPE*,' '
         TYPE*,'Selection out of range.'
       ENDIF
*
* open and create files
```

```
*
*
* begin writing header information
*
      WRITE(5,265)
265   FORMAT(//,'$Enter name of the data file to write to: ',
     +/,'  ERD FORMAT ASSUMED')
      READ(5,267) ERD_FILE_O
267   FORMAT(A32)
* Create the two file names
*
        WRITE(5,4446)
4446    FORMAT('  Enter ERD title?')
        READ(5,4447)ERD_TITLE
4447    FORMAT(A80)
      HDR_FILE_O = ERD_FILE_O
      CALL STR$TRIM(HDR_FILE_O,ERD_FILE_O,LENGTH)
      HDR_FILE_O(LENGTH+1:LENGTH+4) = HDR
      ERD_FILE_O(LENGTH+1:LENGTH+4) = ERD
      OPEN(HDR_UNIT,FILE=HDR_FILE_O,STATUS='UNKNOWN',
     + FORM='FORMATTED',RECL=256)
*
* WRITE OUT HEADER DATA
*
*
*   UNKNOWN KNOWNS
*
      DUMMY = 'ERDFILEV1.00'
      KEYOPT=0
      NLINES=0
      NBIN=-1
      NBIN=-1
      NBYTE=-1
      COMMA=','
      WRITE(HDR_UNIT,270) DUMMY
270   FORMAT(A12)
      WRITE(HDR_UNIT,280) ERD_TITLE
280   FORMAT(A80)
      WRITE(HDR_UNIT,290) NCHAN,COMMA,NSAMP,COMMA,NLINES,COMMA,NBIN,
     &          COMMA,NBYTE,COMMA,KEYNUM,COMMA,STEP,COMMA,KEYOPT
290   FORMAT(6(I7,A),E13.6,A,I7)
      WRITE(HDR_UNIT,300) SCALE(1),((COMMA,SCALE(J)),J=2,NCHAN)
300   FORMAT(18(E13.6,A))
      WRITE(HDR_UNIT,300) OFFSET(1),((COMMA,OFFSET(J)),J=2,NCHAN)
      WRITE(HDR_UNIT,310) (SHORT_NAME(J),J=1,NCHAN)
310   FORMAT(31(A8))
      WRITE(HDR_UNIT,320) (LONG_NAME(J),J=1,NCHAN)
320   FORMAT(7(A32))
      WRITE(HDR_UNIT,310) (UNIT_NAME(J),J=1,NCHAN)
*
* write 9+ lines to file
*
C      TYPE*,' '
      IF(NLINES .EQ. 0) GOTO 330
*      TYPE*,'Enter additional descriptor lines'
       DO 330 J=1,NLINES
*         READ(5,280) LONG
        WRITE(HDR_UNIT,6560)J,SHORT_NAME(J),RMS(J),SMEAN(J)
6560    FORMAT(' CHAN ',I2,3X,A8,3X,' RMS= ',E15.3,4X,' MEAN= ',E15.3)
330      CONTINUE
*
```

```
      CLOSE(HDR_UNIT)
* write  data to file
*
      IF (KEYNUM .EQ. 5) THEN
        OPEN(ERD_UNIT,FILE=ERD_FILE_O,FORM='FORMATTED',
     +   STATUS='UNKNOWN', RECL=256)
        ELSE
        OPEN(ERD_UNIT,FILE=ERD_FILE_O,FORM='UNFORMATTED',
     +  STATUS='UNKNOWN', RECL=256)
        ENDIF
* 2 byte integer
*
      IF (KEYNUM .EQ. 0) THEN
         DO 350 J=1,NSAMP
        WRITE(ERD_UNIT,ERR=406)
     +                 (IIFIX(DATA(L,J)),L=1,NCHAN)
350        CONTINUE
*
* 4 byte floation - binary
*
      ELSE IF (KEYNUM .EQ. 1) THEN
        DO 370 J=1,NSAMP
           WRITE(ERD_UNIT,ERR=406)
     +                (DATA(L,J),L=1,NCHAN)
370        CONTINUE
*
* 8 byte floating - binary
*
      ELSE IF(KEYNUM .EQ. 2) THEN
        DO 390 J=1,NSAMP
        WRITE(ERD_UNIT,ERR=406)
     +            (DBLE(DATA(L,J)),L=1,NCHAN)
390        CONTINUE
*
* formatted output
*
      ELSE
        DO 410 J=1,NSAMP
          WRITE(ERD_UNIT,405,ERR=406)
     +                   (DATA(L,J),L=1,NCHAN)
410        CONTINUE
405     FORMAT(19(E13.6))
        GOTO 35
406     WRITE(5,407) J-1
407     FORMAT(/,' There were ',I10,' records written out before the fi
     +le filled up.',/,' Change NSAMP in the header file accordingly.')
      ENDIF
 35   CLOSE(ERD_UNIT)
*
      RETURN
*
      END
```

# APPENDIX B
# LIST OF FORTRAN PROGRAM FOR FREQUENCY RESPONSE ANALYSIS

```
                              PROGRAM BODE
***************************************************************************
********  Written by   A. L. HELINSKI, US ARMY TACOM  AMSTA-RY   ********
********                                                          ********
***************************************************************************
**************                                     ***********************
******    FOURIER ROUTINES were developed by IEEE "Programs    **********
******    for Digital signal processing."  Although any Fast   **********
******    Fourier program which determines the Real and        **********
******    Imaginary Fourier coefficients from a time           **********
******    history could be used.                               **********
***************************************************************************
*   PURPOSE
*
*   This program is used to plot the frequency response of either
*   the results of a simulated model or by directly putting in
*   the polynomial transfer function coefficients.  The simulated
*   model option must have the ERD file of the results.  Simulation
*   must involve using the sum of sine waves as input.  The resulting
*   file of the output of the transfer function time history must be
*   in ERD format.  In addition the sum of sine waves (Input of transfer
*   function) will be re-generated by giving the same table of
*   frequencies used in the simulation.
*
*   In addition the option is available to design cascade compensation
*   if the prime frequency response is describing the plant response
*   as shown in the configuration below.  The compensation frequency response
*   can also be plotted separately or combined with the Primary (Plant) to
*   generate a total open loop response for this option.  An option is
*   available to determine crossover points representing stability margins
*
*
*                 +  .  . .  .   open    |---------------|      ____________
*  COMMAND--.              .--X   X ----| COMPENSATION  |----|   PLANT    |____
*                                        |     C(S)      |    | (PRIMARY)  |    |
*                    .    .              |               |    |    P(S)    |    |
*                      ..                |---------------|    |____________|    |
*                 -    |                                                        |
*                      |          TOTAL OPEN LOOP =    C(S) x P(s)              |
*                      |                                                        |
*                      |________________________________________________________|
*
*   OBJECTIVE
*
*   The main objective to developing this program is to have a simple
*   means of observing a frequency response with easy access to changes in
*   the transfer function. (Compensation)  It is also beneficial in
*   designing compensation for a non-linear plant model by supplementing
*   this program with a time domain simulation software package
*   like ACSL or MIMIC.
*
*
***************************************************************************
***************************************************************************
***************************************************************************
*   INPUT SIGNAL VARIABLES
        DIMENSION SINP(10000)     ! TIME HISTORY TO BE GENERATED
        DIMENSION AMPI(50)        ! AMPLITUDE
        DIMENSION DBI(50)         ! DB VALUE
        DIMENSION PHASEI(50)      ! PHASE
        DIMENSION REALI(5000)     ! REAL PART
```

```
        DIMENSION AIMAGI(5000)  ! IMAGINARY PART
        DIMENSION GFREQ(50)     ! TABLE OF FREQUENCIES USED
*   OUTPUT SIGNAL VARIBLES
        DIMENSION SOUT(10000)   ! TIME HISTORY RECORDED FROM ACSL
        DIMENSION AMPO(50)    ! AMPLITUDE
        DIMENSION DBO(50)       ! DB VALUE
        DIMENSION PHASEO(50)    ! PHASE
        DIMENSION REALO(5000)   ! REAL PART
        DIMENSION AIMAGO(5000)  ! IMAGINARY PART
*   TIME & FREQUENCY VALUES
        DIMENSION FREQ_TF(50),FREQ(5000),SIGTIM(10000)
*   TRANSFER FUNCTION VARIABLES
        DIMENSION DB_TF(50),PHASE_TF(50)
** DATA HDR INFO ********************************
        REAL*4 DATA(10000,6)
        CHARACTER*8 UNIT_NAME(6),SHORT_NAME(6)
        CHARACTER*32 LONG_NAME(6)
*
*   POLYNOMIAL INPUTS
*
        REAL N_MAT(20,20)
        INTEGER NODR(20),NPLYS,N_DEG
        REAL POLY_N(40)
*
        REAL D_MAT(20,20)
        INTEGER DODR(20),DPLYS,D_DEG
        REAL POLY_D(40)
*
*
** COMPENSATION POLYS
*
        REAL C_N_MAT(20,20)
        INTEGER C_NODR(20),C_NPLYS,C_N_DEG
        REAL C_POLY_N(40)
*
        REAL C_D_MAT(20,20)
        INTEGER C_DODR(20),C_DPLYS,C_D_DEG
        REAL C_POLY_D(40)
*
**********************************************************************
        INTEGER*4 NPOINT,NSAMP
        CHARACTER*1 REPLY,NORD
        CHARACTER*8 UNITS
        CHARACTER*32 CHANNEL
        CHARACTER*80 NOTE
        CHARACTER*20 FILETIT
**********************************************************************
*
        PI=3.141592654
        SCAL=180./PI
        EPSILON=10.E-30         ! Used for detection of 20LOG(small)
*
*
*******************************************************************
*   INITIALIZE  Set all channels of data to zero
*******************************************************************
          DO 789 J=1,10000
             DO 790 K=1,6
                DATA(J,K)=0.
790          CONTINUE
789       CONTINUE
```

```
*
* Determine the users terminal type for later use.
*
5     WRITE(5,6)
6     FORMAT(///,' Enter the terminal identifier code:',/,
     &          '     1 -->  VT240',/,
     &          '     2 -->  TAB',/,
     &          '     3 -->  TEKTRONIX 40XX',/,
     &          '     4 -->  TEKTRONIX 41XX',/,
     &          '$Enter id: ')
      READ(5,*) ITERM
*
5566  WRITE(5,7050)
7050  FORMAT(///////////////////////////////////,
     +    ' This program evaluates transfer fucntion',
     +    ' frequency response.',/,' It is used to plot frequency',
     +' response and design compensation.',///,
     +' Choose the desired analysis for the PRIMARY frequency',
     +' response (Plant):',///,' (1) ACSL simulation-TIME HISTORY',/,
     +'      Interpolation will be included',/,
     +'      (Must know ERD file generated from ACSL and',/,
     +'         frequency table file used in ACSL)',//,
     +' (2) Enter Frequency/Magnitude/Phase POINTS by hand',/,
     +'      Interpolation will be included',//,
     +' (3) Enter transfer funtion in terms of POLYNOMIAL',/,
     +'      COEFFICIENTS',///,' Enter 1, 2 or 3')
*
      READ(5,*)IMENU1
*
*     Label channels to this program's channel
*     configuration for later use.
*
        NCHAN=6
        LONG_NAME(1)='GAIN_PRIME_FREQUENCY_RESPONSE'
        LONG_NAME(2)='PHASE_PRIME_FREQUENCY_RESPONSE'
        LONG_NAME(3)='GAIN_COMPENSATION_FREQUENCY_RESPONSE'
        LONG_NAME(4)='PHASE_COMPENSATION_FREQUENCY_RESPONSE'
        LONG_NAME(5)='GAIN_TOTAL_CASCADE_FREQUENCY_RESPONSE'
        LONG_NAME(6)='PHASE_TOTAL_CASCADE_FREQUENCY_RESPONSE'
*
        SHORT_NAME(1)=' '
        SHORT_NAME(2)=' '
        SHORT_NAME(3)=' '
        SHORT_NAME(4)=' '
        SHORT_NAME(5)=' '
        SHORT_NAME(6)=' '
*
        UNIT_NAME(1)='DB'
        UNIT_NAME(2)='DEG'
        UNIT_NAME(3)='DB'
        UNIT_NAME(4)='DEG'
        UNIT_NAME(5)='DB'
        UNIT_NAME(6)='DEG'
*
*    Enter a note (title)
*
      WRITE(5,5290)
5290  FORMAT(' Enter a NOTE for this run ')
      READ(5,5294)NOTE
5294  FORMAT(A80)
*
```

```
************************************************************************
*          OPTION 1    FREQUENCY RESPONSE FROM TIME HISTORY          *
*                      This option used generally for a non-          *
*                      linear model where a time history can          *
*                      be generated.   Simulation must be from        *
*                      sum of sine wave response                      *
*                                                                     *
*                      Need:                                          *
*                              1.   ERD file of output time history.  *
*                                   (Created from ACSL)               *
*                                                                     *
*                              2.   Table file which contains the     *
*                                   frequencies used to generate      *
*                                   the input.                        *
************************************************************************
          IF(IMENU1 .EQ. 1)THEN
*
*        ------READ INPUT FILE
*        Read the data file containing the time history of the output
*        signal of the transfer function.  The transfer function (model)
*        must be executed by a input containing a sum of sine waves for this
*        option.
*
           CALL READERD(SIGTIM,SOUT,NPOINT,CHANNEL,UNITS)
*
*          ----- Deterine Fourier Coefficients
*          Fourier subroutine computes the fourier coefficients of the output
*          signal in terms of Real and Imaminary terms (Cos & Sin) for each
*          frequency.
*
           CALL FOURIER(SIGTIM,SOUT,NPOINT,REALO,AIMAGO,FREQ,MM)
*
**       READ FREQUENCIES AND GENERATE THE INPUT SIGNAL (The same
*         as it was done in ACSL.)
*
*        -----Read the same frequency table as ACSL
*         Re-generate the same input signal which was used to excite the model.
*         (Due to memory limitation it was easier to re-generate the signal then
*         to create it in the data file.)
*
           CALL READFREQ(GFREQ,GLEVEL,NTABLE)
*
*         ----- Generate Sum of Sin Waves of corresponding frequencies.
*
          DO 771 II=1,NPOINT
             T=SIGTIM(II)
             CALL GENERATE(SINPQ,GFREQ,GLEVEL,NTABLE,T)
             SINP(II)=SINPQ
771       CONTINUE
*
*         -----  Call Fourier for input signal
*         Fourier subroutine determines the fourier coefficients of the input
*         signal.   Theoretically;
*                                   Real          (Cos Term)   =  0.
*                                   Imaginary     (Sin Term)   = GVEVEL
*
          CALL FOURIER(SIGTIM,SINP,NPOINT,REALI,AIMAGI,FREQ,MM)
**
**       DETERMINE AMPLITUDE AND PHASE FOR ONLY THE FREQUENCIES USED
*
          INDEX=1
```

```
      DO 8945 II=1,MM
***************************************************************************
**** First round off frequency to the nearest milli-Hz           *********
**** Note- For example it avoids the problem of 4.999 Hz         *********
**** not being recognized as 5 Hz.                               *********
***************************************************************************
           FREQ(II)=INT(FREQ(II)*1000.+.5)/1000.
*
***************************************************************************
*  Now determine if the frequency is one included in the original        *
*  generated input signal to include in new array of data.               *
***************************************************************************
*
*   ----  Determine if the frequency is included member of roster
*   If the frequency is the same as one generated in the input signal
*   (Included in roster- Freq-Table member used in input generation) then
*   create in the record (Freq-Mag-Phase) otherwise go to next frequency.
*
          IF(FREQ(II) .EQ. GFREQ(INDEX))THEN
*
*  Create new frequency array
*
           FREQ_TF(INDEX)=FREQ(II)
*
*  Create amplitude array of input    *
*
           AMPI(INDEX)=SQRT(REALI(II)**2+AIMAGI(II)**2)
*
*  Create dB array.
*  Avoid LOG10 of very small numbers
*
           IF(AMPI(INDEX) .LT. EPSILON)THEN
              DBI(INDEX)=-580.        ! -580 Db is small, make as limit
           ELSE
              DBI(INDEX)=20.*ALOG10(AMPI(INDEX))
           ENDIF
*
*   Create amplitude and dB array of output signal *
*
           AMPO(INDEX)=SQRT(REALO(II)**2+AIMAGO(II)**2)
           IF(AMPO(INDEX) .LT. EPSILON)THEN
              DBO(INDEX)=-580.        ! -580 Db is small, make as limit
           ELSE
              DBO(INDEX)=20.*ALOG10(AMPO(INDEX))
           ENDIF
*
*   Create Phase array of input and output signal
*
          IF(REALI(II) .EQ. 0.)THEN
           IF(AIMAGI(II) .LT. 0.)THEN
            PHASEI(INDEX)=-90.
           ELSE
            PHASEI(INDEX)=90.
           ENDIF
*
** DETERMINE WHICH QUADRANT THE INPUT PHASE IS IN
*
*
        ELSEIF(REALI(II) .GT. 0. .AND. AIMAGI(II) .GT. 0.)THEN
          RATIOI=ABS(AIMAGI(II)/REALI(II))
          PHASEI(INDEX)=       SCAL*ATAN(RATIOI)
```

```
          ELSEIF(REALI(II) .LT. 0. .AND. AIMAGI(II) .GT. 0.)THEN
            RATIOI=ABS(AIMAGI(II)/REALI(II))
            PHASEI(INDEX)=180. - SCAL*ATAN(RATIOI)
          ELSEIF(REALI(II) .LT. 0. .AND. AIMAGI(II) .LT. 0.)THEN
            RATIOI=ABS(AIMAGI(II)/REALI(II))
            PHASEI(INDEX)=180. + SCAL*ATAN(RATIOI)
          ELSEIF(REALI(II) .GT. 0. .AND. AIMAGI(II) .LT. 0.)THEN
            RATIOI=ABS(AIMAGI(II)/REALI(II))
            PHASEI(INDEX)=360. - SCAL*ATAN(RATIOI)
*
             ENDIF
*
*    OUTPUT PHASE
*
*
             IF(REALO(II) .EQ. 0.)THEN
               IF(AIMAGO(II) .LT. 0.)THEN
                PHASEO(INDEX)=-90.
               ELSE
                PHASEO(INDEX)=90.
               ENDIF
*
*     DETERMINE WHICH PHASE THE OUTPUT IS IN
*
*
             ELSEIF(REALO(II) .GT. 0. .AND. AIMAGO(II) .GT. 0.)THEN
              RATIOO=ABS(AIMAGO(II)/REALO(II))
              PHASEO(INDEX)=         SCAL*ATAN(RATIOO)
             ELSEIF(REALO(II) .LT. 0. .AND. AIMAGO(II) .GT. 0.)THEN
              RATIOO=ABS(AIMAGO(II)/REALO(II))
              PHASEO(INDEX)=    180. - SCAL*ATAN(RATIOO)
             ELSEIF(REALO(II) .LT. 0. .AND. AIMAGO(II) .LT. 0.)THEN
              RATIOO=ABS(AIMAGO(II)/REALO(II))
              PHASEO(INDEX)=    180. + SCAL*ATAN(RATIOO)
             ELSEIF(REALO(II) .GT. 0. .AND. AIMAGO(II) .LT. 0.)THEN
              RATIOO=ABS(AIMAGO(II)/REALO(II))
              PHASEO(INDEX)=    360. - SCAL*ATAN(RATIOO)
*
             ENDIF
*
*    Create dB and phase array of transfer function
*
             DB_TF(INDEX)=DBO(INDEX)-DBI(INDEX)
             PHASE_TF(INDEX)=PHASEO(INDEX)-PHASEI(INDEX)
*
             INDEX=INDEX+1
*
*
          ENDIF
*
8945       CONTINUE
*
*
*    WHICH DELTA F INTERPLOATE
*
        WRITE(5,4659)FREQ_TF(1)
4659    FORMAT(///////,
     +         ' ENTER A DELTA-F(In Hz) FOR INTERPOLATION?',
     +         ' Choose smaller or equal to ',F10.4)
        READ(5,*)STEP
*
```

```
*
*    ---- Interpolate data
*     Interpolate the frequency response data, more points will be generated
*     for a constant step (Delta Hz).  This is done for plotting purposes used
*     later.
*
          F_END=FREQ_TF(INDEX-1)
          NSAMP=INDEX-1
          CALL INTEP(1,NSAMP,STEP,FREQ_TF,DB_TF,PHASE_TF,DATA)
*
          NSAMP=NSAMP-1  ! TRYING TO ELIMINATE ONE MYSTERIOUS BULLSHIT POINT
*
***     FORM TOTAL OPEN LOOP
*       Add primary and Compensation
*
         DO 44333 J=1,NSAMP
              DATA(J,5)=DATA(J,1)+DATA(J,3)
              DATA(J,6)=DATA(J,2)+DATA(J,4)
44333     CONTINUE
*
*
        ENDIF  ! OPTION IMENU1=1
*****************************************************************
*           OPTION 2 ENTER DATA POINTS                          *
*****************************************************************
*       This option is available when only a few frequency data points are
*       known. (Usually from test data or extracted from a plot.)  This option
*       will interpolate points in between the given ones.  Be sure to include
*       enough points to desribe the response.  The more drastic the changes the
*       more points required.
*
        IF(IMENU1 .EQ. 2)THEN
               WRITE(5,3000)
3000           FORMAT(' Enter how many points to enter by hand',
     +                ' (This contains each Frequency, Gain and Phase as',
     +' one point)')
         READ(5,*)NPTS
         DO 3002 J=1,NPTS
           WRITE(5,3003)J
3003       FORMAT(' POINT ',I2,' Enter FREQ(Hz),MAG(dB),PHASE(Deg)')
           READ(5,*)FREQ_TF(J),DB_TF(J),PHASE_TF(J)
3002     CONTINUE
*
        WRITE(5,4669)FREQ_TF(1)
4669    FORMAT(//////,
     +          ' ENTER A DELTA-F(In Hz) FOR INTERPOLATION?',
     +          ' Choose smaller or equal to ',F10.4)
        READ(5,*)STEP
*
        F_END=FREQ_TF(INDEX)
*
         CALL INTEP(1,J,STEP,FREQ_TF,DB_TF,PHASE_TF,DATA)
*
***     FORM TOTAL OPEN LOOP
*
          DO 99333 J=1,NSAMP
              DATA(J,5)=DATA(J,1)+DATA(J,3)
              DATA(J,6)=DATA(J,2)+DATA(J,4)
99333     CONTINUE
*
        ENDIF ! OPTION 2 (POINTS BY HAND)
```

```
***********************************************************************
**** OPTIION 3  ENTER PRIME FREQ BY POLYNOMIALS ******************
*    This option gives the frequency response for a transfer function
*    model described by polynomials in the S (Laplace) domain.
***********************************************************************
         IF(IMENU1 .EQ. 3)THEN
          CALL ENTER_NPOLYS(N_MAT,NODR,NPLYS,N_DEG)  ! ASK NUMERATOR
          CALL ENTER_DPOLYS(D_MAT,DODR,DPLYS,D_DEG)  ! ASK DENOMINATOR
          CALL MULTIPLY_POLYS(N_DEG,NODR,NPLYS,N_MAT,POLY_N) ! MULTIPLY NUM
          CALL MULTIPLY_POLYS(D_DEG,DODR,DPLYS,D_MAT,POLY_D) ! MULTIPLY DEN
*
          WRITE(5,4689)
4689      FORMAT(///////,
     +          ' ENTER A DELTA-F(In Hz) FOR INTERPOLATION?',/,
     +          ' ( .1 Generally Used )')
          READ(5,*)STEP
*
          WRITE(5,5689)
5689      FORMAT(///////////////////////////,
     +         ' ENTER THE END FREQUENCY (SPAN) In Hz ?',/,
     +         ' (100. Generally Used)')
          READ(5,*)F_END
*
*        ----- Poly Response
*        Determine the frequency response for the Numerator and Denominator
*        Product Polynomial (Poly_N & Poly_D respectively).  Find response for
*        frequency range STEP to F_END by STEP.  The channels for the Primary
*        response are 1 & 2 for Gain and Phase respectively.
*
          CALL POLY_RESPONSE(N_DEG,POLY_N,D_DEG,POLY_D,STEP,
     +          F_END,1,2,DATA,NSAMP)
*
***      ---- FORM TOTAL OPEN LOOP
*        By adding the Primary and Compensation response.  (Cascade)
*
          DO 7333 J=1,NSAMP
               DATA(J,5)=DATA(J,1)+DATA(J,3)
               DATA(J,6)=DATA(J,2)+DATA(J,4)
7333      CONTINUE
*
*
         ENDIF   ! OF OPTION 3
***********************************************************************
*                              2ND MENU                               *
***********************************************************************
*
901      WRITE(5,900)
900      FORMAT(///////////////////////////////////////,
     +   '*******  SECOND MENU  ******',///,
     +   ' (1) PLOT frequency response',/,
     +   ' (2) Enter COMPENSATION by polynomials',/,
     +   ' (3) CHECK OR EDIT polynomials',/,
     +   ' (4) Determine CROSSOVERS for total response',/,
     +   ' (5) Enter NEW PRIME FREQUENCY RESPONSE',/,
     +   ' (6) STOP / QUIT',///,
     +   '     Select 1,2,3,4,5 or 6')
         READ(5,*)IMENU2
***********************************************************************
*   OPTION 1 (2ND MENU)       PLOT FREQUENCY RESPONSE                 *
***********************************************************************
         IF(IMENU2 .EQ. 1)THEN
```

```
          CALL TF_PLOT(ITERM,NOTE,NSAMP,STEP,NCHAN,DATA,LONG_NAME,
     +    UNIT_NAME)
          GOTO 901
        ENDIF   ! IMENU2 1ST OPTION
*******************************************************************
*   OPTION 2 (2ND MENU)       ENTER COMPENSATION POLYS            *
*******************************************************************
*
*         Enter compensation by means of transfer function polynomials
*         in S (Laplace) domain, same technique used above for option 3
*         of entering primary response.
*
       IF(IMENU2 .EQ. 2)THEN
         CALL ENTER_NPOLYS(C_N_MAT,C_NODR,C_NPLYS,C_N_DEG)
         CALL ENTER_DPOLYS(C_D_MAT,C_DODR,C_DPLYS,C_D_DEG)
         CALL MULTIPLY_POLYS(C_N_DEG,C_NODR,C_NPLYS,C_N_MAT,C_POLY_N)
         CALL MULTIPLY_POLYS(C_D_DEG,C_DODR,C_DPLYS,C_D_MAT,C_POLY_D)
         CALL POLY_RESPONSE(C_N_DEG,C_POLY_N,C_D_DEG,C_POLY_D,
     +                  STEP,F_END,3,4,DATA,NSAMP)
*
***    ----- FORM TOTAL OPEN LOOP
*      by adding primary and compensation reponse (Cascade)
*
        DO 9333 J=1,NSAMP
            DATA(J,5)=DATA(J,1)+DATA(J,3)
            DATA(J,6)=DATA(J,2)+DATA(J,4)
9333    CONTINUE
*
        GOTO 901
*
      ENDIF   ! IMENU2 2ND OPTION
*************************************************************************
*   OPTION 3 (2ND MENU)       EDIT/LIST POLYNOMIALS                     *
*************************************************************************
*
      IF(IMENU2 .EQ. 3)THEN
*
         IF(IMENU1 .EQ. 3)THEN
           WRITE(5,3335)
3335       FORMAT(///////////////////////////,
     +     '    CHECK/EDIT:',//,'    (1) PRIMARY TRANSFER FUNCTION',//,
     +           '     (2) COMPENSATION TRANSFER FUNCTION',///,
     +     '      ENTER 1 or 2')
           READ(5,*)ICOMP
         ELSE
           ICOMP=2
         ENDIF
*******************************************************************
*                                                                 *
*          LIST PRIMARY POLYS                                     *
*                                                                 *
*******************************************************************
      IF(ICOMP .EQ. 1)THEN
*
*     --- List individual polynomials
*
         WRITE(5,5550)
5550     FORMAT(/////////////////////////////////////,
     +   '*********   PRIMARY NUMERATOR POLYS   ***********',//)
         CALL LIST_POLY(1,N_MAT,POLY_N,NODR,NPLYS,N_DEG)
*
```

```
          WRITE(5,5551)
 5551     FORMAT(//////////////////////////////////////,
     +   '*********  PRIMARY DENOMINATOR POLYS **********',//)
          CALL LIST_POLY(1,D_MAT,POLY_D,DODR,DPLYS,D_DEG)
*
*  LIST PRODUCT POLYS, unless the same as above
*
          IF(NPLYS .GT. 1)THEN
           WRITE(5,4441)
 4441      FORMAT(/////////////////////////////////////,
     +     '********* PRIMARY PRODUCT NUMERATOR POLYNMIAL *',
     +     '*********',//)
           CALL LIST_POLY(2,N_MAT,POLY_N,NODR,1,N_DEG)
          ENDIF
          IF(DPLYS .GT. 1)THEN
           WRITE(5,4442)
 4442      FORMAT(/////////////////////////////////////,
     +     '********* PRIMARY PRODUCT DENOMINATOR POLYNOMIAL',
     +     ' *********',//)
           CALL LIST_POLY(2,D_MAT,POLY_D,DODR,1,D_DEG)
          ENDIF
*
       ELSEIF(ICOMP .EQ. 2)THEN
**********************************************************************
*               LIST COMPENSATION POLYS                              *
*                                                                    *
**********************************************************************
          WRITE(5,5530)
 5530     FORMAT(//////////////////////////////////////,
     +   '********  COMPENSATION NUMERATOR POLYS  ********',//)
          CALL LIST_POLY(1,C_N_MAT,C_POLY_N,
     +                        C_NODR,C_NPLYS,C_N_DEG)
          WRITE(5,5531)
 5531     FORMAT(//////////////////////////////////////,
     +   '********  COMPENSATION DENOMINATOR POLYS *******',//)
          CALL LIST_POLY(1,C_D_MAT,C_POLY_D,
     +                        C_DODR,C_DPLYS,C_D_DEG)
*
*  LIST PRODUCT POLYS, unless the same as above
*
          IF(NPLYS .GT. 1)THEN
           WRITE(5,5534)
 5534      FORMAT(/////////////////////////////////////,
     +     '******** COMPENSATION PRODUCT NUMERATOR *******',//)
           CALL LIST_POLY(2,C_N_MAT,C_POLY_N,C_NODR,1,C_N_DEG)
          ENDIF
          IF(DPLYS .GT. 1)THEN
           WRITE(5,5537)
 5537      FORMAT(/////////////////////////////////////,
     +     '********  COMPENSATION PRODUCT DENOMINATOR ****',//)
           CALL LIST_POLY(2,C_D_MAT,C_POLY_D,C_DODR,1,C_D_DEG)
          ENDIF   ! DPLYS .GT. 1
**************************************************************************
**************************************************************************
**************************************************************************
*
       ENDIF  ! ICOMP 1 or 2
*
************************************************************************
**             EDIT POLYNOMIAL                                         *
************************************************************************
```

```
*
        WRITE(5,5555)
5555    FORMAT(///////////////////////////////////////////////,
     +    '   Do you want to make a change? (Y or N)')
        READ(5,77777)REPLY
77777   FORMAT(A)
*
        IF(REPLY .EQ. 'Y' .OR. REPLY .EQ. 'y')THEN
*
**    NUMERATOR OR DENOMINATOR **************
*
*.............................................................
*
        WRITE(5,66666)
66666   FORMAT(//////////////////////////////////////////////,
     +    '  Changes in the NUMERATOR or DENOMINATOR ? (N or D)')
        READ(5,18)NORD
18      FORMAT(A)
*
         IF(ICOMP .EQ. 1)THEN
           IF(NORD .EQ. 'N' .OR. NORD .EQ. 'n')THEN
**************************************************************
*  CHANGE PRIME POLY & RESPONSE                              *
**************************************************************
*--------  CHANGE PRIME NUMERATOR -------------
              CALL EDIT_POLY(1,N_MAT,NODR,NPLYS,N_DEG)
           ELSEIF(NORD .EQ. 'D' .OR. NORD .EQ. 'd')THEN
*
*--------  CHANGE PRIME DENOMINATOR -----------
              CALL EDIT_POLY(2,D_MAT,DODR,DPLYS,D_DEG)
           ENDIF
*
*  RECREATE FREQUENCY RESPONSE FOR PRIME AND TOTAL
*
              CALL MULTIPLY_POLYS(N_DEG,NODR,NPLYS,N_MAT,POLY_N)
              CALL MULTIPLY_POLYS(D_DEG,DODR,DPLYS,D_MAT,POLY_D)
              CALL POLY_RESPONSE(N_DEG,POLY_N,D_DEG,POLY_D,STEP,
     +            F_END,1,2,DATA,NSAMP)
              DO 3333 J=1,NSAMP
                DATA(J,5)=DATA(J,1)+DATA(J,3)
                DATA(J,6)=DATA(J,2)+DATA(J,4)
3333          CONTINUE
**************************************************************
*
        ELSE   ! ICOMP MUST EQ 2
**************************************************************
*  CHANGE COMPENSATION POLY & RESPONSE                       *
**************************************************************
*--------  CHANGE COMPENSATION NUMERATOR --------
           IF(NORD .EQ. 'N' .OR. NORD .EQ. 'n')THEN
              CALL EDIT_POLY(1,C_N_MAT,C_NODR,C_NPLYS,C_N_DEG)
*
*--------  CHANGE COMPENSATION DENOMINATOR ------
           ELSEIF(NORD .EQ. 'D' .OR. NORD .EQ. 'd')THEN
              CALL EDIT_POLY(2,C_D_MAT,C_DODR,C_DPLYS,C_D_DEG)
           ENDIF
*
*  RECREATE FREQUENCY RESPONSE FOR COMPENSATION AND TOTAL
*
              CALL MULTIPLY_POLYS(C_N_DEG,C_NODR,C_NPLYS,
     +                            C_N_MAT,C_POLY_N)
```

```
*
                CALL MULTIPLY_POLYS(C_D_DEG,C_DODR,C_DPLYS,
     +                               C_D_MAT,C_POLY_D)
*
                CALL POLY_RESPONSE(C_N_DEG,C_POLY_N,C_D_DEG,
     +                    C_POLY_D,STEP,F_END,3,4,DATA,NSAMP)
*
*       ----  CREATE TOTAL OPEN LOOP
*       by adding primary and compensation response (Cascade)
*
                DO 45333 J=1,NSAMP
                  DATA(J,5)=DATA(J,1)+DATA(J,3)
                  DATA(J,6)=DATA(J,2)+DATA(J,4)
45333           CONTINUE
***********************************************************************
*..................................................................
           ENDIF
*
          ENDIF   ! MAKE CHANGES
*
       GOTO 901
*
       ENDIF   ! END OF LIST & EDIT POLYNOMIAL
*

*****************************************************************************
*   OPTION 4 (2ND MENU)       DETERMINE CROSS OVERS FOR CASCADE RESPONSE  *
*****************************************************************************
       IF(IMENU2 .EQ. 4)THEN
         CALL CROSS_OVER(5,NSAMP,STEP,DATA)
         GOTO 901
       ENDIF
***********************************************************************
*   OPTION 5 (2ND MENU)       RETURN TO MAIN MENU
***********************************************************************
       IF(IMENU2 .EQ. 5)THEN
         GO TO 5566
       ENDIF
***********************************************************************
*
       STOP
       END         !   END OF MAIN PROGRAM 'BODE'
*-----------------------------------------------------------------------
***********************************************************************
*********************************************************************
*******************   SUBROUTINE SECTION   ***********************
*********************************************************************
*-----------------------------------------------------------------------
**************************************************************************
***********************************************************************
***********************************************************************
      SUBROUTINE READFREQ(GFREQ,GLEVEL,NTABLE)
*
*     Written by A. L. Helinski  US TACOM  AMSTA-RY
*
*     This subroutine reads the frequency table used by the time domain
*     simulation (ACSL) to create the input signal to excite the transfer
*     function.
*
*      INPUT;  None (File Table Name)
*      OUTPUT;  GFREQ(Index)   Table Frequencies (Hz) (Frequency of each sin wave)
```

```
*               GLEVEL          Amplitude of each sine wave (1 value for all)
*               NTABLE          Number of Sin Waves (Frequencies)
*
      REAL GFREQ(50)
      CHARACTER*30 FILEN
*
      WRITE(5,100)
100   FORMAT(//////////////////////////////,
     +      '  Enter The File with the frequency table?',/,
     +      '  Example:  freqs.dat')
      READ(5,140)FILEN
140   FORMAT(A30)
      OPEN(10,FILE=FILEN,FORM='FORMATTED',SHARED,
     + STATUS='OLD',ERR=210)
      READ(10,400)GLEVEL
400   FORMAT(/,G10.4)
      NTABLE=1
800   READ(10,600)GFREQ(NTABLE)
600   FORMAT(G10.4)
      IF(GFREQ(NTABLE) .LT. 0.)GOTO 300
      NTABLE=NTABLE+1
      GOTO 800
210   WRITE(5,170)
170   FORMAT(' ERROR OPENING FILE')
300   CLOSE(10)
      RETURN
      END

      SUBROUTINE GENERATE(SINPUT,GFREQ,GLEVEL,NTABLE,T)
*
*     Written by A. L. Helinski  US TACOM  AMSTA-RY
*
*    This subroutine creates the sweep wave (Sum of sine waves)
*    for creating the input signal to a frequency response
*    analysis to determine transfer function characteristics.
*
*       INPUT:  GFREQ   Table of Frequencies
*               GLEVEL  Amplitude for all
*               NTABLE  Number of Sine waves (Frequencies)
*      OUTPUT;  SINPUT  Sum of sine wave signal (Signal Generated)
*                T       Corresonding Time (Seconds)
*
*
      DIMENSION GFREQ(50)
      SINPUT=0.
      PI=3.141592654
      DO 100 II=1,NTABLE
         SINPUT=SINPUT + GLEVEL*SIN(2*PI*T*GFREQ(II))
100   CONTINUE
      RETURN
      END
*****************************************************************
*****************************************************************
******************************************************************
******************************************************************
      SUBROUTINE INTEP(ICHAN,NSAMP,DELTA_F,FREQ,DB,PHASE,DATA)
*
*       Written by A. L. Helinski   US TACOM  AMSTA-RY
*
**********************     INTERPOLOLATION    ***********************
*   This subroutine interpolates points from the frequency response results
```

```
*   (Gain and Phase) to re-establish data with a constant step
*   (Delta Freq. Hz) so that the further processes will be adaptible.
*   In other words this program basically converts a set of raw data
*   of varied steps (Varied Sampling Rates) to a set of data with constant
*   step.  If you think that sounds hairy, wait until you see the data!
*   Warning must be a sufficient number of points to begin with, enter
*   at your own risk.  The more drastic the changes in the data the
*   more points will be required.
******************************************************************************
*        INPUT;  ICHAN       Index for channel   ICHAN will be gain
*                                                and ICHAN+1 will be phase
*                NSAMP       Number of samples
*                DELTA_F     Desired Step frequency (Hz)
*                FREQ        Actual frequency of points for Phase & DB
*                            before interpolation. (Un-interpolated points)
*                DB          dB values of un-interpolated points
*                PHASE       Phase (Deg) values of un-interpolated points
*
*       OUTPUT;  NSAMP               New number of samples for interpolated
*                                    results   (Changed from input)
*                DATA(ISAMP,ICH)     New interpolated data with constant step
*
*       Generate slopes and intercepts from the frequency selected
*       points.
*
      DIMENSION PHASE(50),DB(50),FREQ(50)
      DIMENSION DB_SL(50),DB_IT(50)
      DIMENSION PHASE_SL(50),PHASE_IT(50)
      REAL*4 DATA(10000,6)
      INTEGER*4 NSAMP
*
      DO 1999 J=1,NSAMP-1
          PHASE_SL(J) =
     +     (PHASE(J+1)-PHASE(J))/(FREQ(J+1)-FREQ(J))
          PHASE_IT(J) =
     +     PHASE(J)-PHASE_SL(J)*FREQ(J)
          DB_SL(J) =
     +     (DB(J+1)-DB(J))/(FREQ(J+1)-FREQ(J))
          DB_IT(J) =
     +     DB(J)-DB_SL(J)*FREQ(J)
1999   CONTINUE
          FREQFIN=FREQ(NSAMP)
*
*   DETERMINE NEW INTERPLOATED DATA
*
       NSAMP=INT(FREQFIN/DELTA_F-1)
       STEP=DELTA_F
*
       J=1
       DO 7510 K=1,NSAMP
          FREQN=DELTA_F*(K-1)
          FREQO=FREQ(J)
          IF(FREQN .GT. FREQO)THEN
           J=J+1
          ENDIF
          DATA(K,ICHAN)=DB_SL(J)*FREQN+DB_IT(J)
          DATA(K,ICHAN+1)=PHASE_SL(J)*FREQN+PHASE_IT(J)
7510   CONTINUE
       RETURN
       END
******************************************************************************
```

```
********************************************************************************
**********************************************************************************
      SUBROUTINE TEK_DELAY
*
*     Written by AL Reid   US TACOM AMSTA-RV   for plotting routine
*
* This subroutine will delay 2 seconds to allow the tektronix screen ample
* time to clear itself.
*
*       INPUT;  NONE
*       OUTPUT; NONE
*
      TNOW = SECNDS(0.0)
10    DELTA = SECNDS(TNOW)
      IF (DELTA .LT. 2.0) GOTO 10
*
      RETURN
      END
*
*
      SUBROUTINE CROSS_OVER(ICH,NSAMP,DELTA_F,DATA)
*******************************************************************
*************  DETERMINE ALL CROSSOVER POINTS  *****************
*******************************************************************
*
*     Written by A. L. Helinski  US TACOM  AMSTA-RV
*
*     This subroutine determines the crossovers of a frequency
*     response data for stability checks for the case when the response
*     is a total open loop.  The process simply scans the DATA array
*     for magnitude (DB) and Phase and detects any crossover points of
*     0 dB or +/-  180 Deg respectively.
*
*        INPUT;  ICH           Index channel as
*                              ICH would be Gain
*                              then ICH1 would be Phase
*
*               NSAMP                              Number of samples
*               DELTA_F                            Step frequency in Hz
*               DATA(SAMP,Channel Number)          Data as Gain or Phase
*
*        OUTPUT; NONE (Results are printed on screen)
*
*        INTERNAL;   SIGN_DB,SIGN_PH    Change of sign indicators
*                    JCRP,JCRG          Index for crossovers
*
        INTEGER*4 NSAMP
        DIMENSION SIGN_DB(10000),SIGN_PH(10000)
        DIMENSION JCRP(10000),JCRG(10000)
        REAL*4 DATA(10000,6)
*
*         DETERMINE ALL POINTS AROUND 0 dB
*
      DO 8199 J=1,NSAMP
*
*
*   DETERMINE ALL POINTS AROUND 0 dB
*
       IF(DATA(J,ICH) .EQ. 0.)THEN
        SIGN_DB(J)=0.
       ELSE
```

```
          SIGN_DB(J)=DATA(J,ICH)/ABS(DATA(J,ICH))
         ENDIF
*
*
*
*    DETERMINE ALL POINTS AROUND -180 DEG
*
         IF(DATA(J,ICH+1) .EQ. -180.)THEN
          SIGN_PH(J)=0.
         ELSE
          IF(DATA(J,ICH+1) .LT. 0.)THEN
            SIGN_PH(J)=(-180.-DATA(J,ICH+1))/ABS(-180.-DATA(J,ICH+1))
          ELSEIF(DATA(J,ICH+1) .GT. 0.)THEN
            SIGN_PH(J)=(-180.+DATA(J,ICH+1))/ABS(-180.+DATA(J,ICH+1))
          ENDIF
         ENDIF
*
8199  CONTINUE
*
*  DETERMINE SIGN CHANGES
*
          ICG=1.
          ICP=1.
        DO 8198 J=1,NSAMP-1
           IF(SIGN_DB(J+1) .NE. SIGN_DB(J))THEN
               JCRG(ICG)=J+1
               ICG=ICG+1
           ENDIF
           IF(SIGN_PH(J+1) .NE. SIGN_PH(J))THEN
               JCRP(ICP)=J+1
               ICP=ICP+1
           ENDIF
8198   CONTINUE
*
*
            WRITE(5,2005)
2005        FORMAT(23X,'******** GAIN CROSSOVERS ******** ',/,
     +          10X,' GAIN(dB)',13X,' PHASE(Deg)',13X,' FREQ(Hz)')
            IF(ICG .EQ. 1)THEN
              WRITE(5,9373)
9373          FORMAT('**  NONE **')
            ELSE
               DO 1666 J=1,ICG-1
                 FHZH=(JCRG(J))*DELTA_F
                 FHZL=(JCRG(J)-1)*DELTA_F
                 WRITE(5,4502)DATA(JCRG(J)-1,ICH),DATA(JCRG(J)-1,ICH+1)
     +                                                            ,FHZL
                 WRITE(5,4502)DATA(JCRG(J),ICH),DATA(JCRG(J),ICH+1),FHZH
4502             FORMAT(6X,F10.4,13X,F10.4,13X,F10.4)
                 WRITE(5,4903)
4903             FORMAT(/)
1666           CONTINUE
            ENDIF
*
            WRITE(5,447)
            READ(5,*)
*
          WRITE(5,1667)
1667      FORMAT(//,23X,'********  PHASE +/- 180DEG CROSSOVERS ******* ',
     +    /,10X,' PHASE(DEG)',13X,' GAIN(DB)',13X,' FREQ(Hz)')
            IF(ICP .EQ. 1)THEN
```

```
        WRITE(5,9365)
9365    FORMAT(/,' ** NONE ** ')
       ELSE
        DO 1234 J=1,ICP-1
          FHZH=(JCRP(J))*DELTA_F
          FHZL=(JCRP(J)-1)*DELTA_F
          WRITE(5,4502)DATA(JCRP(J)-1,ICH+1),DATA(JCRP(J)-1,ICH)
     +                                                        ,FHZL
          WRITE(5,4502)DATA(JCRP(J),ICH+1),DATA(JCRP(J),ICH),FHZH
          WRITE(5,4903)
1234    CONTINUE
       ENDIF
*
       WRITE(5,447)
447    FORMAT(///,' HIT RETURN TO CONTINUE')
       READ(5,*)
*
       RETURN
       END
**********************************************************************
**********************************************************************
       SUBROUTINE ENTER_NPOLYS(N_MAT,NODR,NPLYS,N_ORDER)
*
*      Written by A. L. Helinski US TACOM  AMSTA-RY
*
*      This subroutine will let you enter the polynomials representing
*      the numerator of a transfer function.  It's no different then
*      Subroutine ENTER_DPOLYS.
*
*         INPUT;   NONE  (Enter all output parameters by hand)
*         OUPUT:   N_MAT(POLY#,ORDER#)  Polynomial Coefficients
*                  NODR(POLY#)          Order of each polynomial
*                  NPLYS                Number of Polynomial
*                  N_Order              Total Order (Degree of product)
*                                       Sum of all DODR(POLY#)
*
       REAL N_MAT(20,20)       ! NUM. MATRIX COEFICIENTS(POLY#,ORDER)
       INTEGER NODR(20),NPLYS  ! NUM. ORDER (POLY#) , NUM. # OF POLYS
*
       WRITE(5,10)
10     FORMAT(/////////////////////////////////////////////////,
     +      ' Enter number of polynomials in the numerator?')
       READ(5,*)NPLYS
       WRITE(5,20)
20     FORMAT(//)
       N_ORDER=0
       DO 90 I=1,NPLYS
         WRITE(5,30)I
30       FORMAT(' Enter order of poly #',I2)
         READ(5,*)NODR(I)
         N_ORDER=N_ORDER+NODR(I)   ! ADD TOTAL ORDERS (DEGREE)
         WRITE(5,40)
40       FORMAT(/)
         DO 50 J=NODR(I)+1,1,-1
           WRITE(5,60)J-1
60         FORMAT('      S**',I2,' TERM IS ? ',:)
           READ(5,*) N_MAT(I,J)  ! NUMERATOR MATRIX (POLY#,ORDER+1)
50       CONTINUE
         WRITE(5,70)
70       FORMAT(/)
90     CONTINUE
```

```
*
        RETURN
        END
*****************************************************************
*****************************************************************
        SUBROUTINE ENTER_DPOLYS(D_MAT,DODR,DPLYS,D_ORDER)
*
*       Written by A. L. Helinski  US TACOM  AMSTA-RY
*
*       This subroutine will let you enter the polynomials representing
*       the denominator of a transfer function.  It's no different then
*       Subroutine ENTER_NPOLYS.
*
*          INPUT:  NONE  (Enter all output parameters by hand)
*          OUPUT:  D_MAT(POLY#,ORDER#)  Polynomial Coefficients
*                  DODR(POLY#)          Order of each polynomial
*                  DPLYS                Number of Polynomial
*                  D_Order              Total Order (Degree of product)
*                                       Sum of all DODR(POLY#)
*
        REAL D_MAT(20,20)
        INTEGER DODR(20),DPLYS,D_ORDER
*
        WRITE(5,10)
10      FORMAT(///////////////////////////////////////,
     +     ' Enter number of polynomials in the denominator?')
        READ(5,*)DPLYS
        WRITE(5,20)
20      FORMAT(//)
        D_ORDER=0
        DO 90 I=1,DPLYS
          WRITE(5,30)I
30        FORMAT(' Enter order of poly # ',I2)
          READ(5,*)DODR(I)
          D_ORDER=D_ORDER+DODR(I)
          WRITE(5,40)
40        FORMAT(/)
          DO 50 J=DODR(I)+1,1,-1
            WRITE(5,60)J-1
60          FORMAT('       S**',I2,' TERM IS ?',:)
            READ(5,*) D_MAT(I,J)   ! NUMERATOR MATRIX (POLY#,ORDER+1)
50        CONTINUE
          WRITE(5,70)
70        FORMAT(/)
90      CONTINUE
*
        RETURN
        END
*****************************************************************
*****************************************************************
        SUBROUTINE MULTIPLY_POLYS
     +        (TOTAL_ORDER,POLY_ORDER,NPOLYS,MATRIX,PRODUCT)
*
*       Written by A. L. Helinski US TACOM  AMSTA-RY
*
*   This subroutine multiplies polynomials for resulting product of
*   a single resulting polynomial.  The procedure is much the same way
*   as one would do by hand. (Term by term)
*
* INPUT;     TOTAL_ORDER          Total degree of product was done before hand
*                                 by adding the degree of each polynomial
```

```
*               POLY_ORDER               Degree of each individual polynomial
*               NPOLYS                   Number polynomials
*               MATRIX(POLY#,Order#) Matrix of Polynomial coefficients
*                                        (Simply a 2-D array)
*
* OUTPUT:       PRODUCT(Order #)         Final product polynomial
*
            INTEGER TOTAL_ORDER          ! ORDER OF PRODUCT (OR TOTAL SUM degrees)
            INTEGER POLY_ORDER(20)       ! ORDER OF EACH POLY
            INTEGER NPOLYS               ! NUMBER OF POLYS
            REAL MATRIX(20,20)           ! COEFFICIENTS OF (POLY#,ORDER)
            REAL SM(50)                  ! USED AS SUMMER DURING OPERATION
            REAL PRODUCT(40)             ! PRODUCT RESULTS
*
*           PRODUCT must have a intitial value.  In this program the
*           initial product will be 1.
*
*
            PRODUCT(1)=1.    !  INITIAL PRODUCT WILL BE 1.
*
            LEVL=0
            DO 10 M=1,TOTAL_ORDER+1
               SM(M)=0.        ! SUMMER USED IN MULIPLICATION
10          CONTINUE
*
            DO 20 I=1,NPOLYS
               DO 30 K=1,LEVL+1
                  DO 40 L=1,POLY_ORDER(I)+1
                    SM(K+L-1)=SM(K+L-1) + MATRIX(I,L) * PRODUCT(K)
40                CONTINUE
30             CONTINUE
               DO 50 M=1,TOTAL_ORDER+1
                 PRODUCT(M)=SM(M)
                 SM(M)=0.
50             CONTINUE
                 LEVL=LEVL+POLY_ORDER(I)
20          CONTINUE
*
            RETURN
            END
************************************************************************
************************************************************************
************************************************************************
            SUBROUTINE POLY_RESPONSE(N_DEG,POLY_N,D_DEG,POLY_D,
     +       F_STEP,F_END,NCHAN_MAG,NCHAN_PHASE,DATA,NPTS)
*
*           Written by A. L. Helinski US TACOM  AMSTA-RY
*
*  Determine frequency response for a single polynomial describing the
*  numerator and one describing the denominator of a transfer function for
*  a given frequency range.
*
*           INPUT;     N_DEG              Degree of numerator
*                      POLY_N(Order#)     Coefficients describing numerator poly
*                      D_DEG              Degree of Denominator
*                      POLY_D(Order#)     Coefficients describing denominator poly
*                      F_STEP             Desired delta frequency of range
*                                         Also first frequency point to evaluate
*                      F_END              End frequency of range (Span)
*                      NCHAN_MAG          Desired channel number for Magnitude (dB)
*                      NCHAN_PHASE        Desired channel number for Phase (Deg)
```

```
*
*         OUTPUT;  NPTS                     Number of frequency pts made
*                  DATA(NSAMP,NCHAN)        DATA made
*                     where     Gain (dB)   is DATA(NSAMP,NCHAN_MAG)
*                               Phase (Deg) is DATA(NSAMP,NCHAN_PHASE)
*                               @ frequencies = NSAMP*F_STEP Hz
*
          REAL DREL,DIMG,NREL,NIMG
          REAL PHASEN,PHASED
          REAL*4 DATA(10000,6)
          REAL POLY_D(40),POLY_N(40)
          INTEGER D_DEG,N_DEG
*
          PI=3.141592654
          SCAL=180./PI
          EPSILON=10.E-30
*
          NPTS=INT(F_END/F_STEP)
*
*     DETERMINE GAIN AND PHASE FOR NUMERATOR AND DENOMINATOR
*
          DO 90 JJ=1,NPTS
             FR=F_STEP*JJ
             WR=FR*2.*PI
*  Determine Real and Imaginary components for NUM and DEN
             CALL POLY_REAL_IMAG(NREL,NIMG,WR,N_DEG,POLY_N)
             CALL POLY_REAL_IMAG(DREL,DIMG,WR,D_DEG,POLY_D)
*
*  Determine dB Gain
*
             GAIN=SQRT( (NREL**2+NIMG**2) / (DREL**2+DIMG**2) )
*
             IF(GAIN .LE. EPSILON)THEN
               DATA(JJ,NCHAN_MAG) = -580.
             ELSE
               DATA(JJ,NCHAN_MAG) =  20.* ALOG10(GAIN)
             ENDIF
*
*  Determine PHASE for NUM and DEN
*
*   Numerator
*
             IF(NREL .EQ. 0. .AND. NIMG .LT. 0.)THEN
               PHASEN = -90.
             ELSEIF(NREL .EQ. 0. .AND. NIMG .GT. 0.)THEN
               PHASEN = 90.
             ELSEIF(NIMG .EQ. 0. .AND. NREL .GT. 0.)THEN
               PHASEN = 0.
             ELSEIF(NIMG .EQ. 0. .AND. NREL .LT. 0.)THEN
               PHASEN = 180.
*
             ELSEIF(NREL .GT. 0. .AND. NIMG .GT. 0.)THEN
               RATION=ABS(NIMG/NREL)
               PHASEN=       SCAL*ATAN(RATION)
             ELSEIF(NREL .LT. 0. .AND. NIMG .GT. 0.)THEN
               RATION=ABS(NIMG/NREL)
               PHASEN=180. - SCAL*ATAN(RATION)
             ELSEIF(NREL .LT. 0. .AND. NIMG .LT. 0.)THEN
               RATION=ABS(NIMG/NREL)
               PHASEN=180. + SCAL*ATAN(RATION)
             ELSEIF(NREL .GT. 0. .AND. NIMG .LT. 0.)THEN
```

```
                  RATION=ABS(NIMG/NREL)
                  PHASEN=360. - SCAL*ATAN(RATION)
 *
                ENDIF
 *
 *            DENOMINATOR PHASE
 *
 *
                   IF(DREL .EQ. 0. .AND. DIMG .LT. 0.)THEN
                     PHASED = -90.
                   ELSEIF(DREL .EQ. 0. .AND. DIMG .GT. 0.)THEN
                     PHASED = 90.
                   ELSEIF(DIMG .EQ. 0. .AND. DREL .GT. 0.)THEN
                     PHASED = 0.
                   ELSEIF(DIMG .EQ. 0. .AND. DREL .LT. 0.)THEN
                     PHASED = 180.
 *
                   ELSEIF(DREL .GT. 0. .AND. DIMG .GT. 0.)THEN
                     RATIOD=ABS(DIMG/DREL)
                     PHASED=          SCAL*ATAN(RATIOD)
                   ELSEIF(DREL .LT. 0. .AND. DIMG .GT. 0.)THEN
                     RATIOD=ABS(DIMG/DREL)
                     PHASED=180. - SCAL*ATAN(RATIOD)
                   ELSEIF(DREL .LT. 0. .AND. DIMG .LT. 0.)THEN
                     RATIOD=ABS(DIMG/DREL)
                     PHASED=180. + SCAL*ATAN(RATIOD)
                   ELSEIF(DREL .GT. 0. .AND. DIMG .LT. 0.)THEN
                     RATIOD=ABS(DIMG/DREL)
                     PHASED=360. - SCAL*ATAN(RATIOD)
 *
                ENDIF
 *
 *   Determine Total Phase
 *
                DATA(JJ,NCHAN_PHASE)=PHASEN-PHASED
 *
 90           CONTINUE
 *
              RETURN
              END

***************************************************************************
***************************************************************************
***************************************************************************
              SUBROUTINE POLY_REAL_IMAG(XREAL,XIMAG,OMEG,NORDER,POLY)
*
*         Written by A. L. Helinski  US TACOM  AMSTA-RY
*
*        DETERMINE REAL AND IMAGINARY COMPONENTS FOR A
*        GIVEN FREQUENCY(OMEG) AND POLYNOMIAL
*
*        This subroutine called upon by sub-poly-response to determine the
*        Real and Imaginary components for a given polynomial and frequency(W).
*        It simply plugs in S=jW and resolves the complex algebra. ( W omega in
*        rad/sec and j is complex where j=SQRT [ -1 ]. )
*
*        INPUT:  POLY     (Array of POLY coefficients)
*                NORDER   Order of polynomial
*                OMEG     Frequency in Rad/Sec
*        OUPUT;  XREAL   Real Component
*                XIMAG   Imaginary Component
```

```
*
      REAL POLY(40)
*
         XREAL=0.
         XIMAG=0.
*
         DO 10 II=1,NORDER+1
*
            IORD=II-1
*
            INDEX=IORD
20          IF(INDEX .GE. 4) THEN
               INDEX=INDEX-4
               GO TO 20
            ELSE
*
              IF(INDEX .EQ. 0)THEN
                XREAL=XREAL + POLY(IORD+1)*OMEG**IORD
              ELSEIF(INDEX .EQ. 1)THEN
                XIMAG=XIMAG + POLY(IORD+1)*OMEG**IORD
              ELSEIF(INDEX .EQ. 2)THEN
                XREAL=XREAL - POLY(IORD+1)*OMEG**IORD
              ELSEIF(INDEX .EQ. 3)THEN
                XIMAG=XIMAG - POLY(IORD+1)*OMEG**IORD
              ENDIF
            ENDIF
*
10       CONTINUE
*
         RETURN
         END
************************************************************************
************************************************************************
************************************************************************
         SUBROUTINE LIST_POLY(ID,POLY_MATRIX,PRODUCT_POLY,
     +         ORDER_MATRIX,NUM_POLYS,DEGREE)
*
*       Written by A. L. Helinski   US TACOM  AMSTA-RY
*
*        This subroutine list the polynomial coefficients.
*
*        INPUT;      ID  Identify individual polnomials or single product
*                           If ID = 1   Number of individual Polynomials
*                              ID = 2   Single Product Polynomial
*                    POLY_MATRIX(POLY#,Order #)
*                           Actually describes the coefficints in this
*                           2-D array fashion. (When ID=1 otherwise a dummy)
*
*                    PORDUCT_POLY(Order #)
*                           Decribes a single polynomial in coefficient terms.
*                           (When ID=2 otherwise a dummy variable.)
*
*                    ORDER_MATRIX(POLY #)
*                           Describes the degree for each polynomial
*
*                    NUM_POLYS  Number of polynomials  (=1 for ID=2)
*
*                    DEGREE   Total degree of polynomial (or sum of orders)
*
*       OUTPUT;      None (Just simply lists the polynomials on the screen)
*
```

```
      REAL POLY_MATRIX(20,20),PRODUCT_POLY(40)
      INTEGER ID,ORDER_MATRIX(20),NUM_POLYS,DEGREE,POWER
      INTEGER NUM_POLS
*
      IF(ID .EQ. 2)THEN
        NUM_POLS=1
      ELSE
        NUM_POLS=NUM_POLYS
      ENDIF
*
         WRITE(5,8888)
8888     FORMAT('                 COEFFICIENT TERMS  ',/)
*
         DO 10 IPOLY=1,NUM_POLS
          WRITE(5,20)IPOLY,ORDER_MATRIX(IPOLY)
20        FORMAT('  POLY ',I2,5X,' ORDER =',I2,/,
     +   '---------------------------------------------')
*
          IF(ID .EQ. 1)THEN
            POWER=ORDER_MATRIX(IPOLY)
          ELSEIF(ID .EQ. 2)THEN
            POWER=DEGREE
          ENDIF
*
            DO 40 IORD=POWER+1,1,-1
*
              IF(ID .EQ. 1)THEN
                WRITE(5,70)POLY_MATRIX(IPOLY,IORD),IORD-1
70              FORMAT(5X,F15.8,'  S**',I2)
              ELSE
                WRITE(5,80)PRODUCT_POLY(IORD),IORD-1
80              FORMAT(5X,F15.8,'  S**',I2)
              ENDIF
*
40          CONTINUE
*
10        CONTINUE
*
          WRITE(5,66)
66        FORMAT(//,' HIT RETURN TO CONTINUE')
          READ(5,*)
*
      RETURN
      END
*******************************************************************
*******************************************************************
      SUBROUTINE EDIT_POLY(ID,MATRIX,ORDER,NUM_POLYS,DEG)
*
*        Written by A. L. Helinski  US TACOM  AMSTA-RY
*
*        This subroutine edits the polynomials by changing the
*        coefficient terms individually.
*
*     INPUT;  ID;      IF ID = 1   NUMERATOR TERMS
*                         ID = 2   DENOMINATOR TERMS
*           MATRIX(POLY#,ORDER #);    2-D ARRAY OF POLYNOMIAL COEFFICIENTS
*           ORDER(POLY #);            DEGREE OF EACH POLY#
*           NUM_POLYS                 NUMBER OF POLYNOMIALS
*           DEG;                      TOTAL DEGREE
*     OUTPUT; Same as input with modifications
*
```

```
      REAL MATRIX(20,20)
      INTEGER ID,NUM_POLYS,DEG,ORDER(20)
      CHARACTER*1  REPLY
*
      IF(ID .EQ. 1)THEN
        WRITE(5,10)
10      FORMAT(/////////////////////////////////////////////,
     + ' Do you desire to re-enter the entire NUMERATOR ? (Y or N)')
        READ(5,20)REPLY
20      FORMAT(A)
        IF(REPLY .EQ. 'Y' .OR. REPLY .EQ. 'y')THEN
           CALL ENTER_NPOLYS(MATRIX,ORDER,NUM_POLYS,DEG)
           RETURN
*
        ENDIF
      ELSE
        WRITE(5,30)
30      FORMAT(/////////////////////////////////////////////,
     +  ' Do you desire to re-enter the entire DENOMINATOR ? (Y or N)')
        READ(5,20)REPLY
        IF(REPLY .EQ. 'Y' .OR. REPLY .EQ. 'y')THEN
           CALL ENTER_DPOLYS(MATRIX,ORDER,NUM_POLYS,DEG)
           RETURN
*
        ENDIF
      ENDIF
*
*     Edit Polynomial by terms
*
      IF(NUM_POLYS .GT. 1)THEN
         WRITE(5,70)
70       FORMAT(///////////////////////////////////////////,
     +   ' Which Polynomial do you desire to change ?',/,
     +   ' ( Give the number representing the polynomial sequence )')
         READ(5,*)MPOLY
      ELSE
         MPOLY=1
      ENDIF
*
      IF(ORDER(MPOLY) .GT. 1)THEN
         WRITE(5,80)MPOLY
80       FORMAT(////////////////////////////////////////////,
     +      ' Which ORDER coefficient of S do you desire to ',/,
     +      ' change in POLY # ',I2,'   ?')
         READ(5,*)MCOEFF
      ELSE
         MCOEFF=1
      ENDIF
*
      WRITE(5,90)MATRIX(MPOLY,MCOEFF+1)
90    FORMAT(///////////////////////////////////////////////////////,
     +    '  Change ',F10.4,' TO   ?')
      READ(5,*)MATRIX(MPOLY,MCOEFF+1)
*
      RETURN
      END
*****************************************************************************
*****************************************************************************
      SUBROUTINE READERD(TIME,SIGNAL,NSAMP,
     +          CHANNEL,UNITS,NCH)
*
```

```
*        Written by AL Reid  US TACOM   AMSTA-RY
*        Modified by A. L. Helinski  US TACOM  AMSTA-RY
*
*       This subroutine orignally written by Al Reid and modified by A. L.
*       Helinski.  It simply reads a data file of a time history in ERD file
*       format.   For this application ACSL creates the time data file
*       simulating the output of a transfer function this routine reads the
*       time history into the desired variables by calling it.
*
*       INPUT;     None  (Data File Name)
*       OUTPUT;    SIGNAL    Amplitude of history
*                  TIME      Corresponding Time is Seconds

      DIMENSION TIME(10000),SIGNAL(10000)
      CHARACTER*80 ERD_TITLE,LONG_TITLE,DUMMY80
      CHARACTER*64 ERD_FILE,HDR_FILE,ERD_FILE_O,HDR_FILE_O
      CHARACTER*32 LONG_NAME(6),DUMMY32,CHANNEL
      CHARACTER*12 DUMMY
      CHARACTER*8 SHORT_NAME(6),UNIT_NAME(6),XUNIT,DUMMY8,
     + UNITS
      CHARACTER*4 ERD,HDR
      CHARACTER*1 COMMA,REPLY
      REAL*4 SCALE(6),OFFSET(6),RDATA(6,10000)
      INTEGER*4 NSAMP
      INTEGER*4 START_SAMP_ELIM,END_SAMP_ELIM
      INTEGER*2 ERD_UNIT,HDR_UNIT
      DIMENSION IARRAY(400),IDATA(4)
      DATA ERD_UNIT,HDR_UNIT/10,11/
      ERD = '.ERD'
      HDR = '.HDR'
*
* Determine the name of the input data file
*
10    WRITE(5,20)
20    FORMAT(////,' Enter name of ERD data file to analyze?')
      READ(5,30) ERD_FILE
30    FORMAT(A32)
      CALL STR$TRIM(HDR_FILE,ERD_FILE,LENGTH)
      HDR_FILE(LENGTH+1:LENGTH+4) = HDR
      ERD_FILE(LENGTH+1:LENGTH+4) = ERD
*
* Open the data file, print the header characteristics, and determine if
* this is the correct data file
*
      OPEN(HDR_UNIT,FILE=HDR_FILE,FORM='FORMATTED',
     +        SHARED,STATUS='OLD',ERR=210)
*
* Read the header data
*
      READ(HDR_UNIT,60) DUMMY
60    FORMAT(A12)
      READ(HDR_UNIT,70) ERD_TITLE
70    FORMAT(A80)
      READ(HDR_UNIT,80) NCHAN,COMMA,NSAMP,COMMA,NLINES,COMMA,NBIN,
     +          COMMA,NBYTE,COMMA,KEYNUM,COMMA,STEP,COMMA,KEYOPT
80    FORMAT(6(I7,A),E13.6,A,I7)
      READ(HDR_UNIT,90) SCALE(1),(COMMA,SCALE(L),L=2,NCHAN)
      READ(HDR_UNIT,90) OFFSET(1),(COMMA,OFFSET(L),L=2,NCHAN)
      READ(HDR_UNIT,100) (SHORT_NAME(L),L=1,NCHAN)
      READ(HDR_UNIT,110) (LONG_NAME(L),L=1,NCHAN)
      READ(HDR_UNIT,100) (UNIT_NAME(L),L=1,NCHAN)
```

```
90    FORMAT(18(E13.6,A))
100   FORMAT(31(A8))
110   FORMAT(7(A32))
*
* Write out the header information
*
      WRITE(5,120) ERD_TITLE,NCHAN,NSAMP,STEP
120   FORMAT(//,' The title for this file is:',/,' ',A80,//,' There are
     +',I2,' channels of data.',/,' There are ',I7,' samples for each da
     +ta channel.',/,' The step size is ',F8.5,' seconds.',//)
*
* See if there are more than 16 channels to plot
*
      IF (NCHAN .GT. 16) THEN
         TYPE*,' There are more than 16 channels to read.'
         TYPE*,' Please  FORGET ABOUT IT'
         CLOSE (HDR_UNIT)
         STOP
         ENDIF
*
* Write out the additional descriptor lines
*
      IF (NLINES .GT. 0) THEN
         TYPE*,'The following are the optional descriptor lines:'
         DO 130 L=1,NLINES
            READ(HDR_UNIT,70) LONG
            WRITE(5,125) LONG
125         FORMAT(' ',A80)
130         CONTINUE
         ENDIF
*
* Is this the correct data file
*
      WRITE(5,140)
140   FORMAT(//,'$Is this the correct data file to analyze (y or n)?
     +')
      READ(5,150) REPLY
150   FORMAT(A)
      IF (REPLY .EQ. 'N' .OR. REPLY .EQ. 'n') THEN
         CLOSE(HDR_UNIT)
         WRITE(5,160)
160      FORMAT(/,'$Do you wish to look at another file (y or n)? ')
         READ(5,150) REPLY
         IF (REPLY .EQ. 'N' .OR. REPLY .EQ. 'n') STOP
         GOTO 10
         ENDIF
*
* Open the data part of the file
*
      IF (KEYNUM .EQ. 5) THEN
         OPEN(ERD_UNIT,FILE=ERD_FILE,STATUS='OLD'
     +        ,SHARED,FORM='FORMATTED')
        ELSE
         OPEN(ERD_UNIT,FILE=ERD_FILE,STATUS='OLD'
     +        ,SHARED,FORM='UNFORMATTED')
        ENDIF
      CLOSE(HDR_UNIT)
*
* Read the data
*
      J = 0
```

```
170    J=J+1
          IF (KEYNUM .EQ. 5) THEN

            READ(ERD_UNIT,180,ERR=220,END=230) (RDATA(I,J),I=1,NCHAN)
180         FORMAT(19(E13.6))

          ELSE

            IF (KEYNUM .EQ. 0) THEN
              READ(ERD_UNIT,ERR=220,END=230) (IDATA(I),I=1,NCHAN)
              DO 190 K=1,NCHAN
                RDATA(K,J) = FLOATJ(IDATA(K))
190             CONTINUE
             ELSE
              READ(ERD_UNIT,ERR=220,END=230) (RDATA(I,J),I=1,NCHAN)
             ENDIF

          ENDIF

          GOTO 170
*
*
*
210    TYPE*,'Error opening data file'
       STOP
*
220    TYPE*,'Error reading data in file'
230    CLOSE(ERD_UNIT)
*
*
*********** DATA IS READ IN, NOW START EVALUATION *******
*
*** Convert UNscaled and UNbiased data to proper values
       DO 6002 I=1,NCHAN
          DO 6003 J=1,NSAMP
             RDATA(I,J) = RDATA(I,J) / SCALE(I) + OFFSET(I)
6003      CONTINUE
             SCALE(I)=1.
             OFFSET(I)=0.
6002     CONTINUE
*
567        WRITE(5,1018)
1018       FORMAT(//,'***** CHANNELS *******',//)
           DO 1050 JI=1,NCHAN
           IF(JI .EQ. 6 .OR. JI .EQ. 12 .OR. JI .EQ. 18 .OR.
     +     JI .EQ. 24 .OR. JI .EQ. 30 .OR. JI .EQ. 36) THEN
             WRITE(5,1032)
             READ(5,*)
           ENDIF
           WRITE(5,1060)JI,LONG_NAME(JI),UNIT_NAME(JI)
1060       FORMAT(/,' CHANNEL ',I2,/,1X,A32,/,1X,A8)
1050       CONTINUE
           WRITE(5,1032)
1032       FORMAT(/,'*********  HIT RETURN ********')
           READ(5,*)
***
           WRITE(5,1081)
1081       FORMAT(' ENTER CHANNEL NUMBER TO ANALYZE')
           READ(5,*)NCHANPSD
***
             UNITS=UNIT_NAME(NCHANPSD)
```

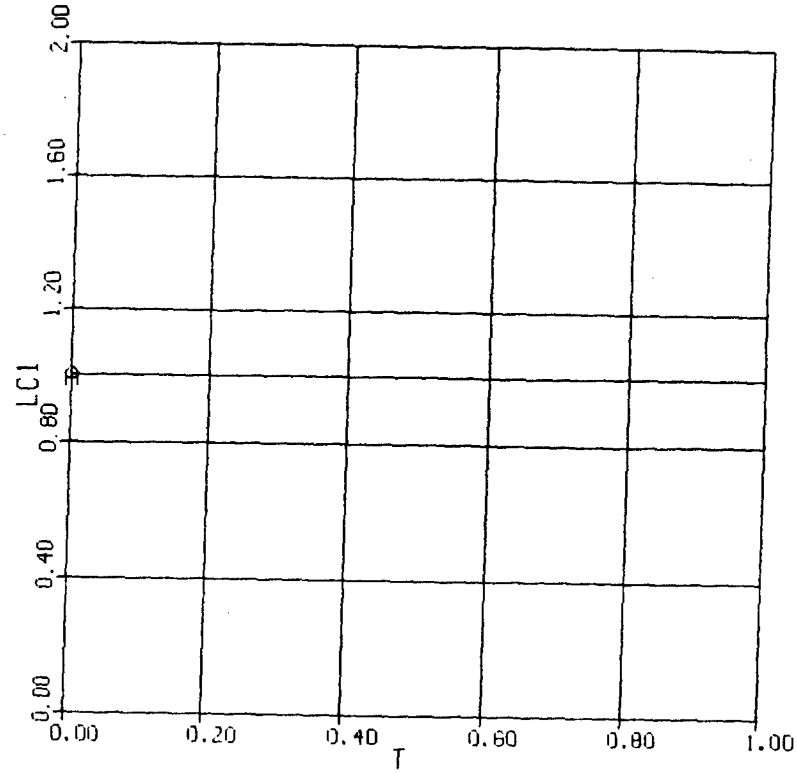
```
          CHANNEL=LONG_NAME(NCHANPSD)
*
*       DETERMINE TIME ARRAY FROM STEP
*
          DO 1061 I=1,NSAMP
           TIME(I)=STEP*(I-1)
           SIGNAL(I)=RDATA(NCHANPSD,I)
1061      CONTINUE
*
          RETURN
          END
*******************************************************************
*******************************************************************
*******************************************************************
      SUBROUTINE TF_PLOT(ITERM,ERD_TITLE,NSAMP,STEP,NCHAN,DATA,
     +    LONG_NAME,UNIT_NAME)
*
*
*       Must insert a subroutine for plotting ERD data format.
*       This particular application uses a PLOT10 Library routine
*       (Not Included).  It is advised to use a subroutine which has
*       a graphics mode capable of plotting semi-log graphs.
*       The following format of input variables was used.
*
*    INPUT:  ITERM                       ID for terminal
*            ERD_TITLE                   Title for plot ('NOTE' from main)
*            NSAMP                       Number of samples
*            STEP                        Delta F (Hz)
*            NCHAN                       Number of Channels  (6 for this program)
*            DATA(Nsamp,Channel Number)  Data in amplitude
*            LONG_NAME(Channel Number)   Name for channel
*            UNIT_NAME(Channel Number)   Unit for channel
*    OUTPUT; None  (A plot on the screen!  what else do you expect!!!)
*
*
*     TF_PLOT Subroutine...
*
      RETURN
      END
*
*******************************************************************
*******************************************************************
******    FOURIER SECTION   ***************************************
*******************************************************************
*******************************************************************
        SUBROUTINE FOURIER(X,Y,NPT,REAL,AIMAG,FREQ,MM)
*
*       Must insert a fourier analysis subroutine.
*       The one used for this analysis was developed by IEEE for
*       digital processing.  (Not included)
*       It determines the fourier coefficients for a time
*       history.  The essential requirement is that the time history be
*       described by a Power-Of-2-Number-Of-Points.
*
*        INPUT;       Y (Nsamp)   Signal in Amplitude
*                     X (Nsamp)   Corresponding Time (Seconds)
*                     NPT         Corresponding Number Of points of signal
*                                 (Program will help you choose closest
*                                  power of 2)
*        OUPUT:       REAL      Real Coefficient         (Cos Term)
*                     AIMAG     Imaginary Coefficient    (Sin Term)

*                     FREQ      Corresponding Frequency (Hz)
*                     MM        Number of points in frequency domain.
*
*        FOURIER Subroutine...
*
         RETURN
         END
```

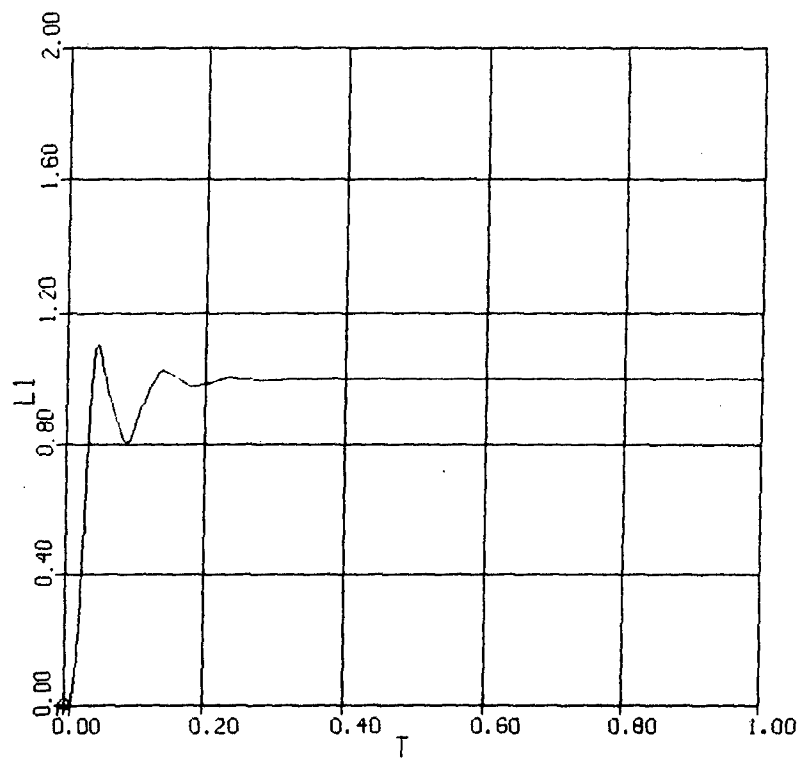
APPENDIX C
VARIOUS STATES OF A STEP RESPONSE

## STEP RESPONSE 1 IN

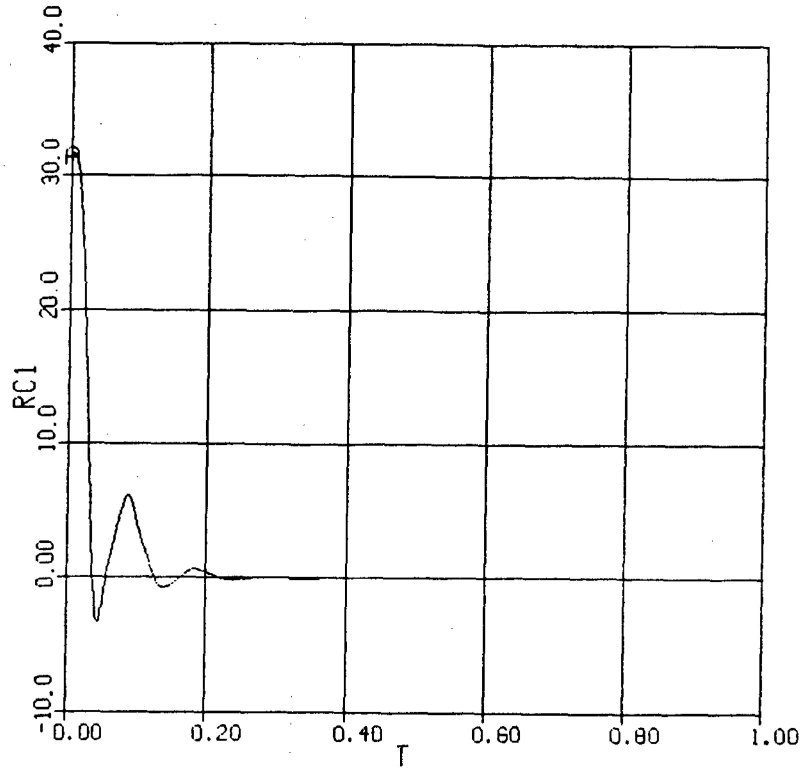
### POSITION COMMAND



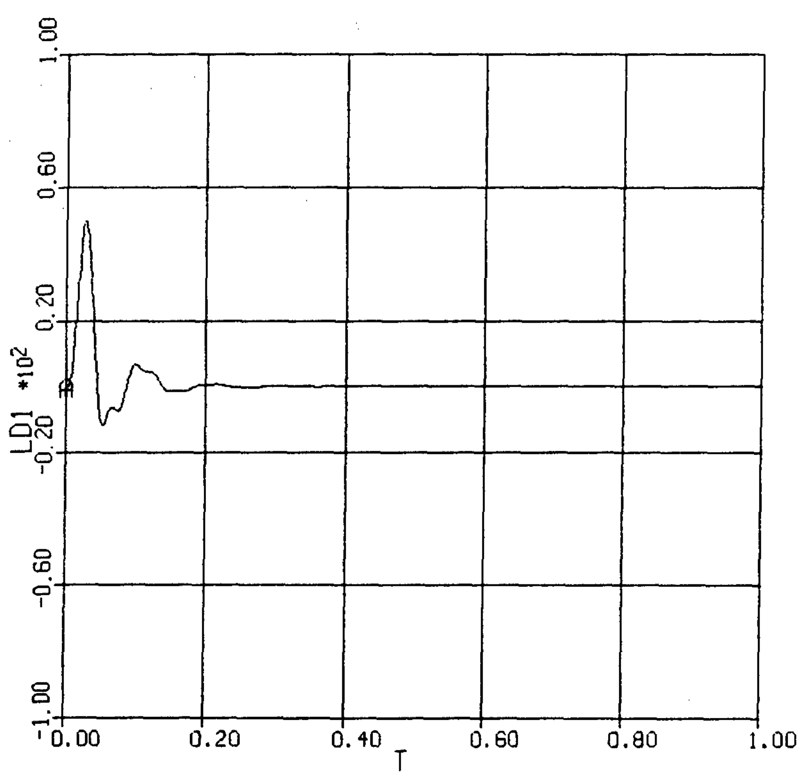

### POSITION RESPONSE



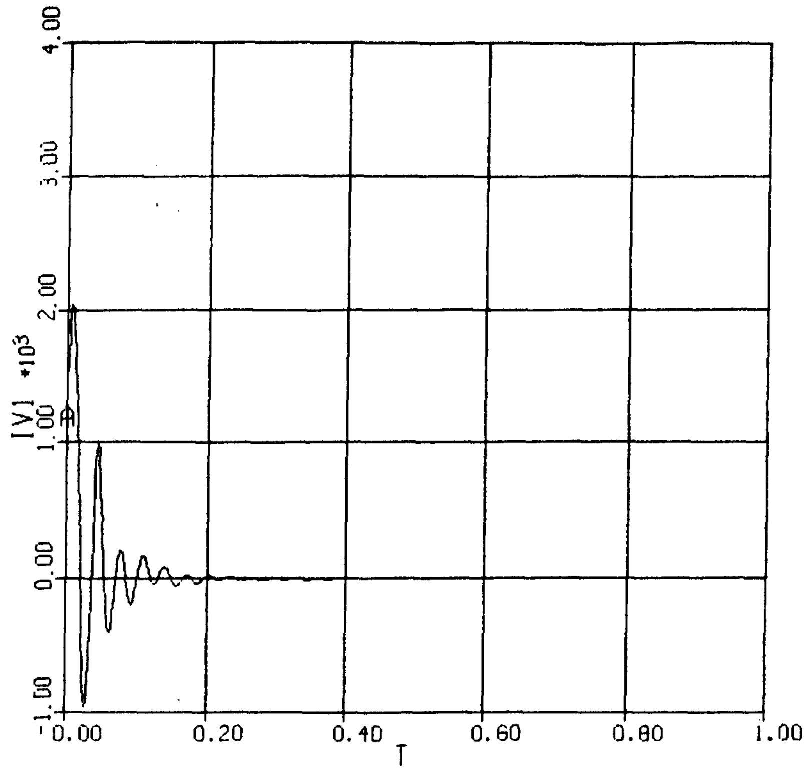
**RATE COMMAND**



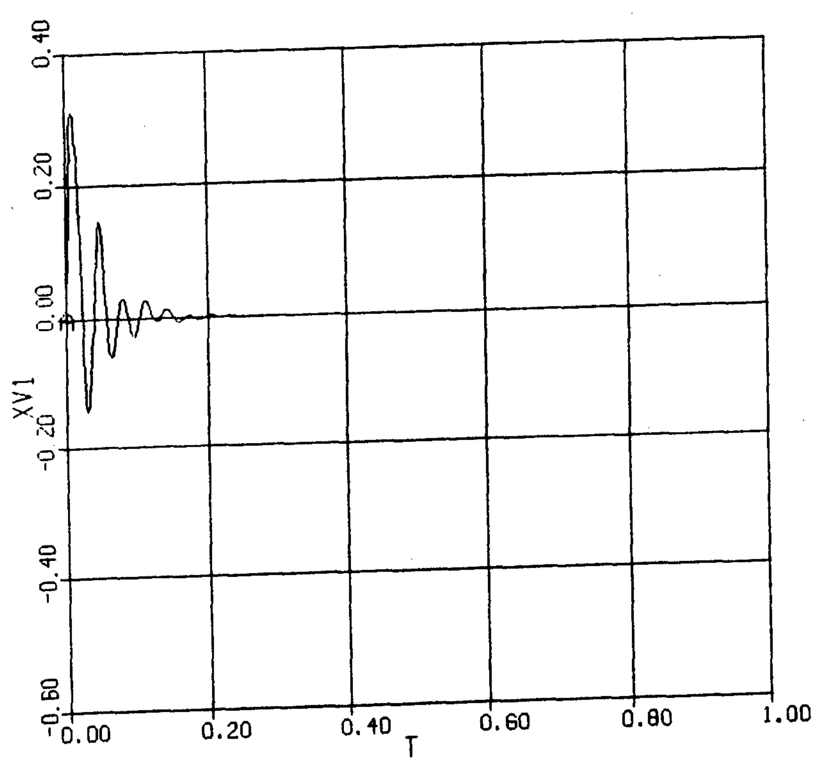

**RATE RESPONSE**



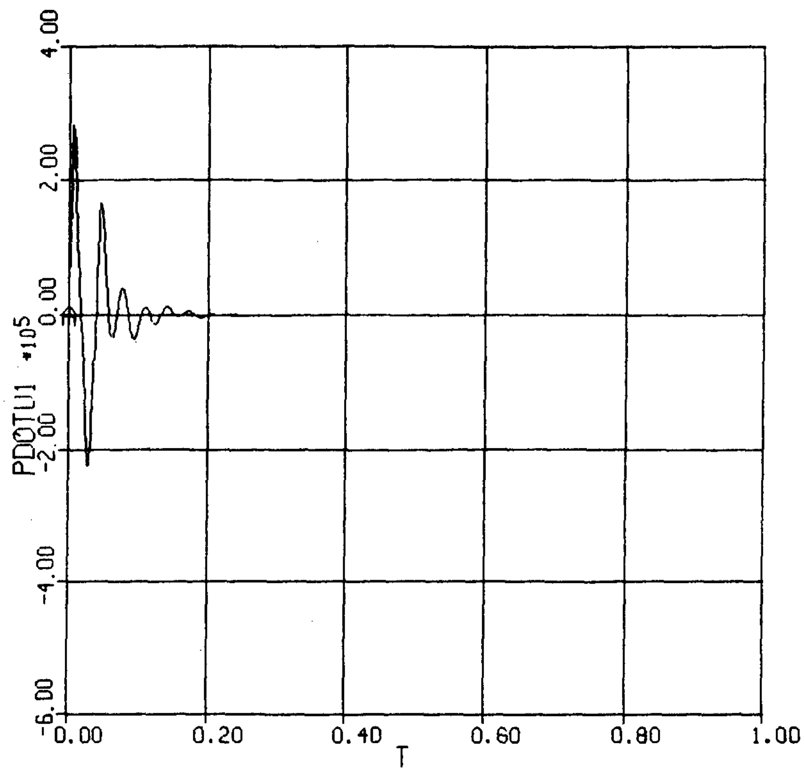
**SERVO INPUT CURRENT**



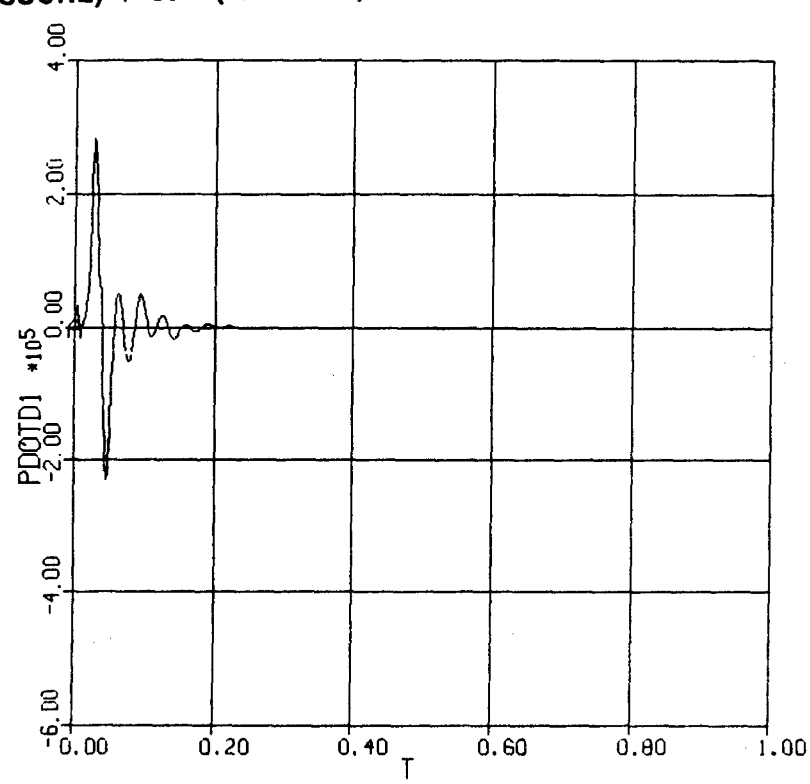

**SPOOL POSITION**



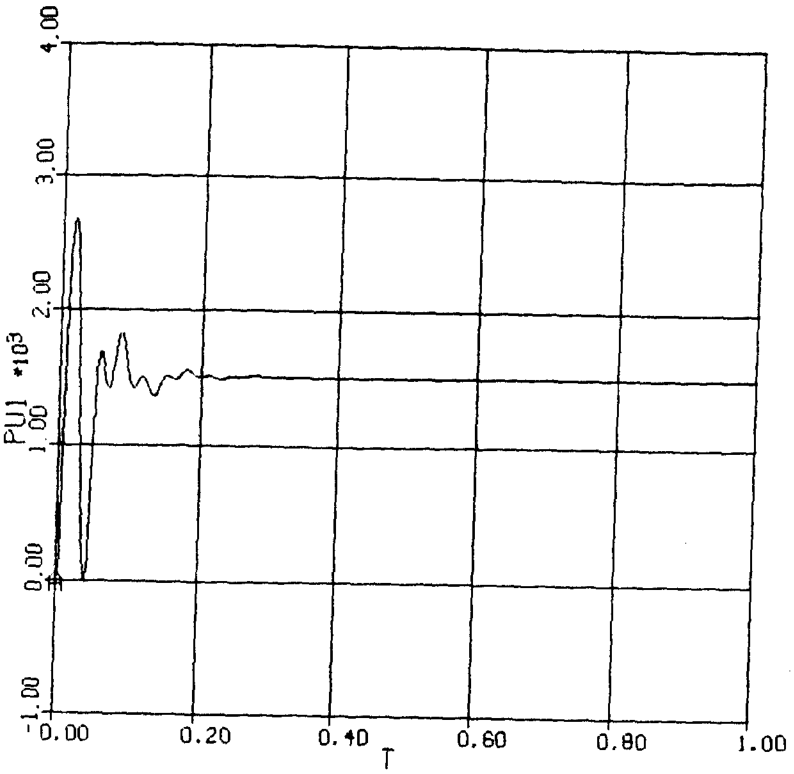
∂ (PRESSURE) / ∂t (for up)



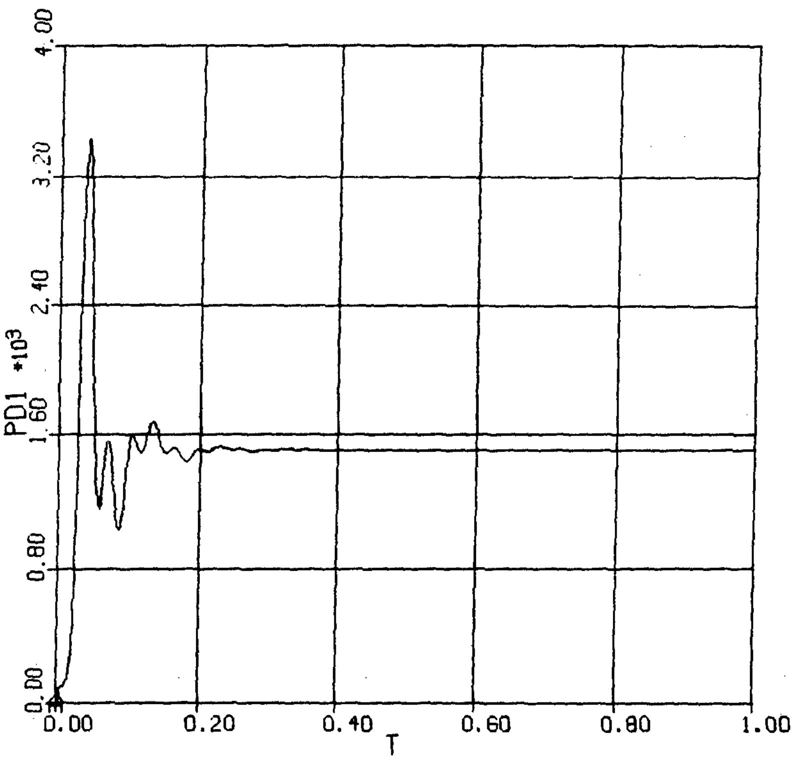

∂ (PRESSURE) / ∂t (for down)



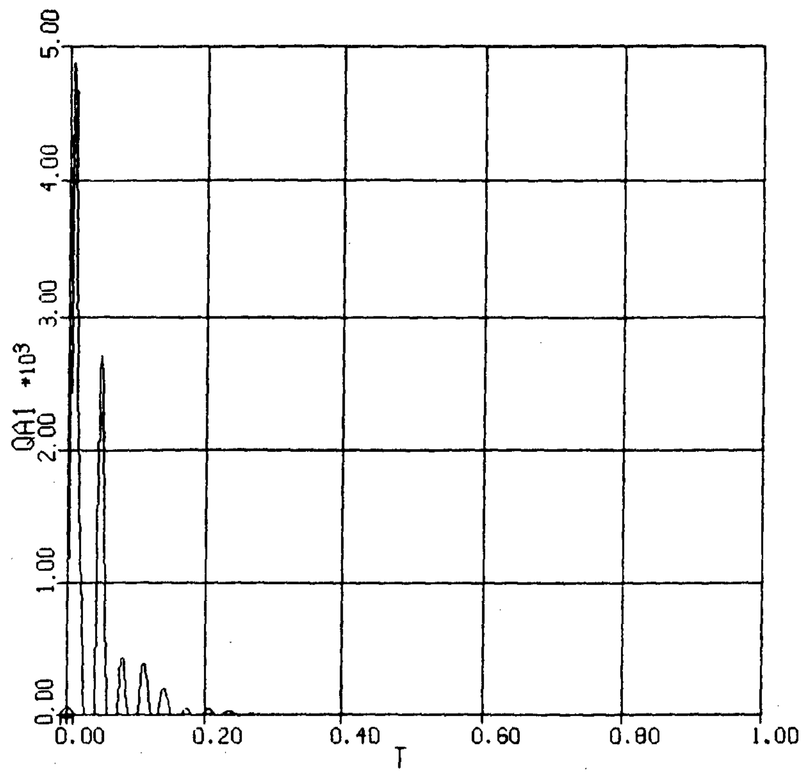
ACTUATOR PRESSURE (for up)



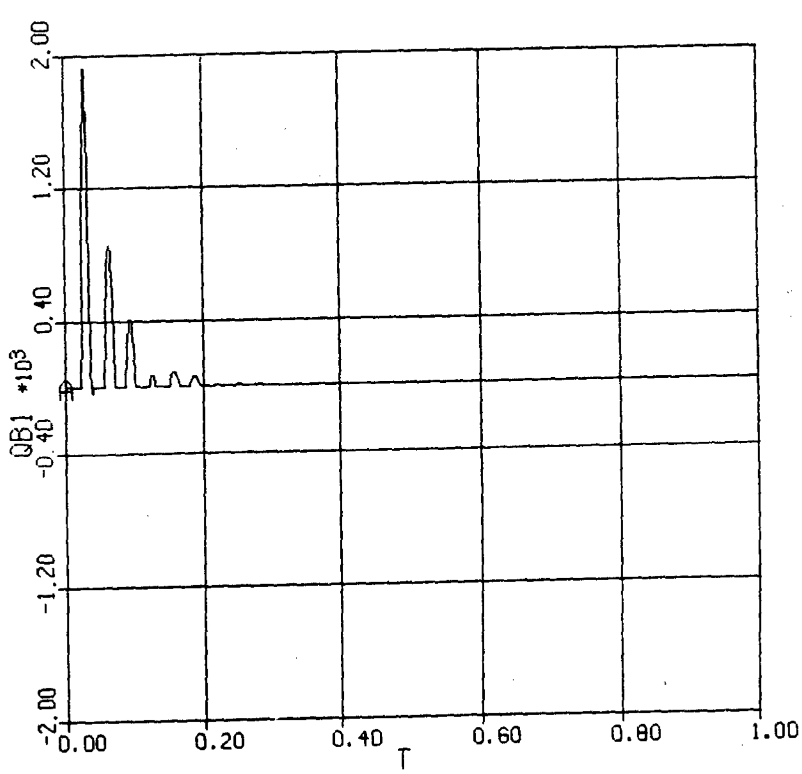

ACTUATOR PRESSURE (for down)



**FLOW IN (for up)**

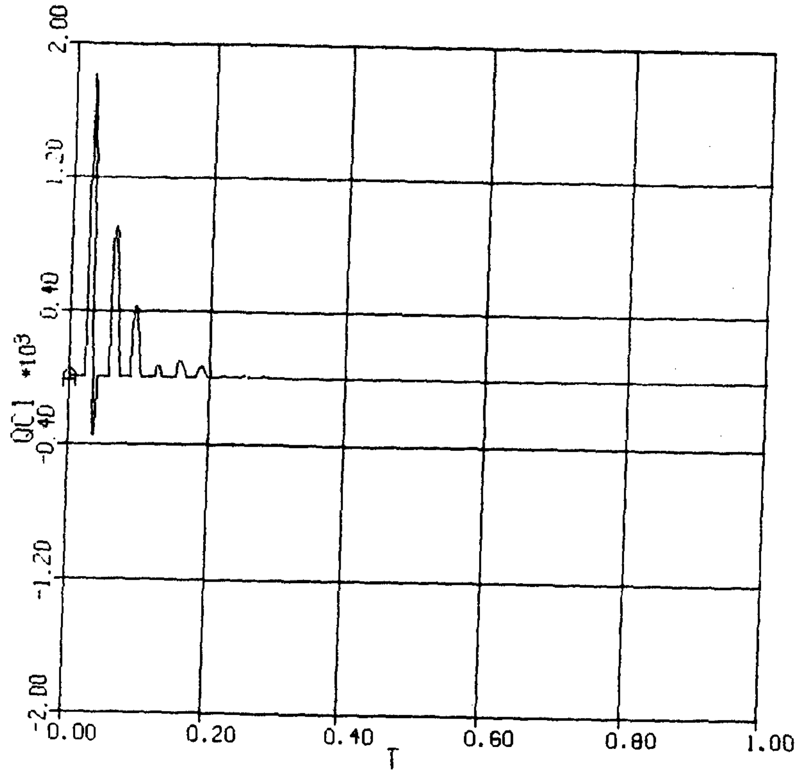



**FLOW OUT (for up)**

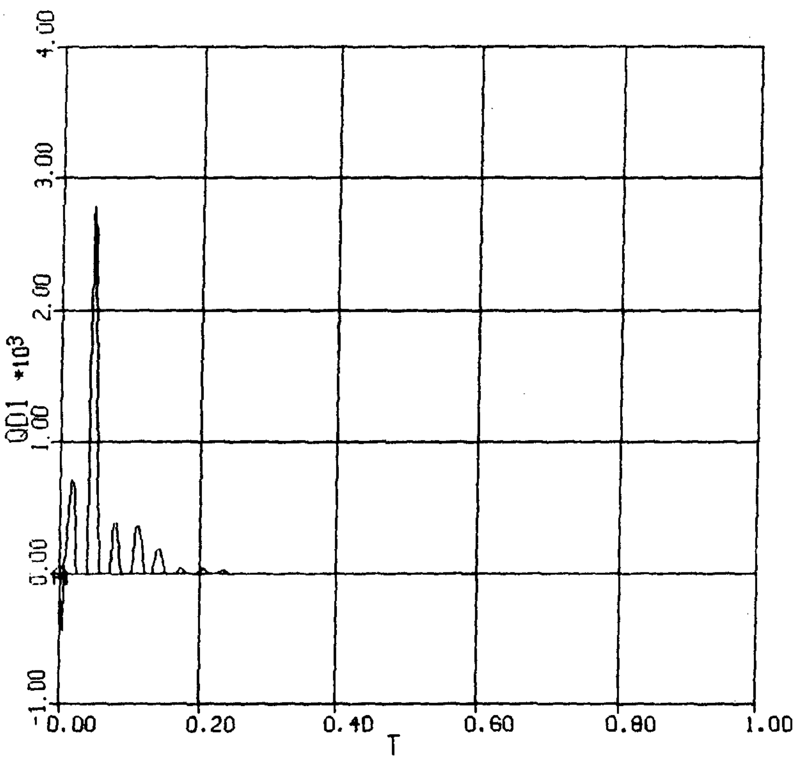


## STEP RESPONSE 1 IN

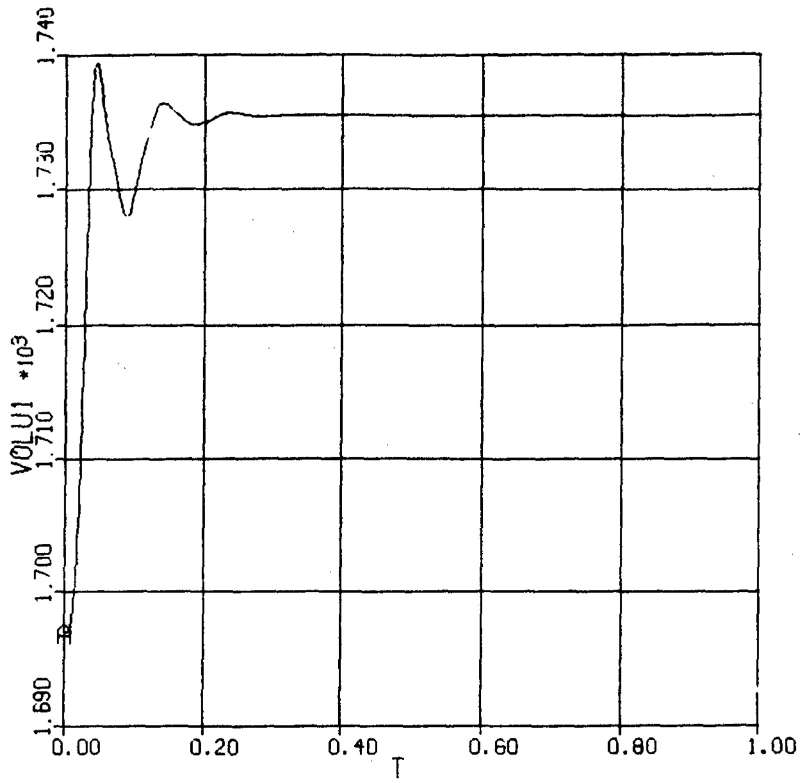
FLOW IN (for down)



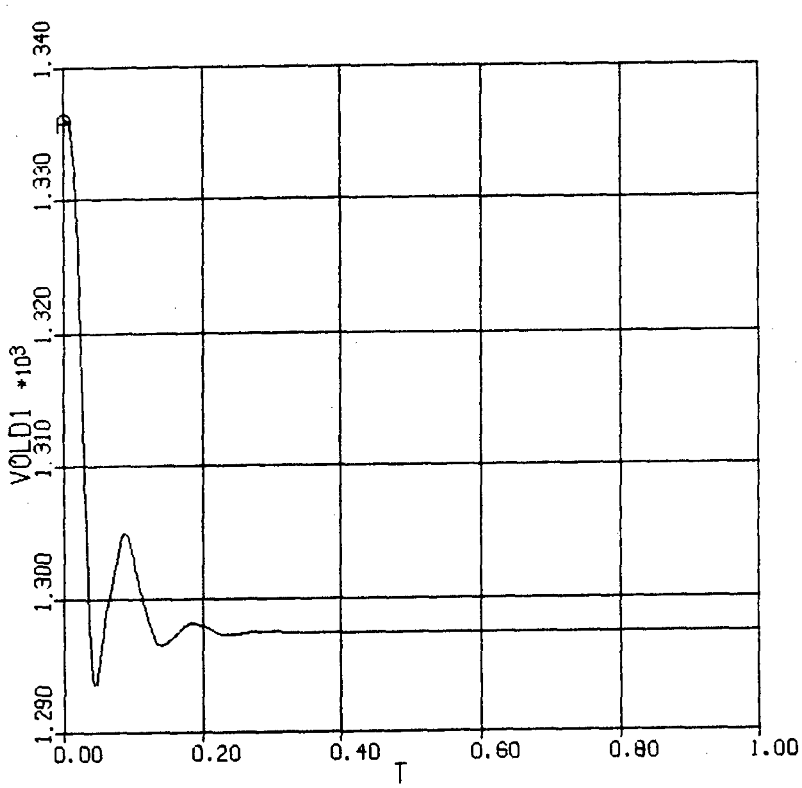

FLOW OUT (for down)



ENTRAINED VOLUME (for up)

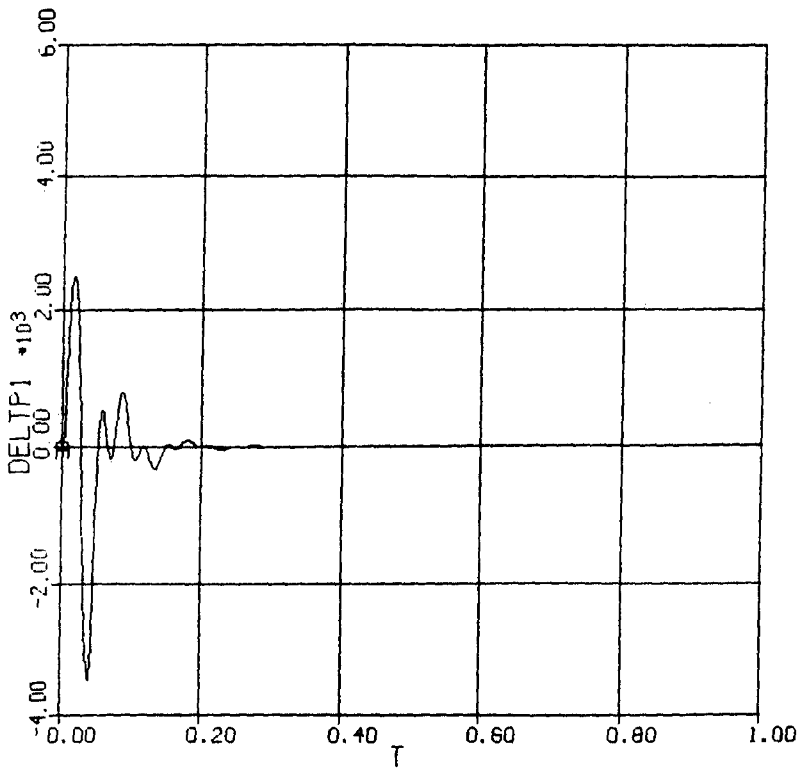



ENTRAINED VOLUME (for down)

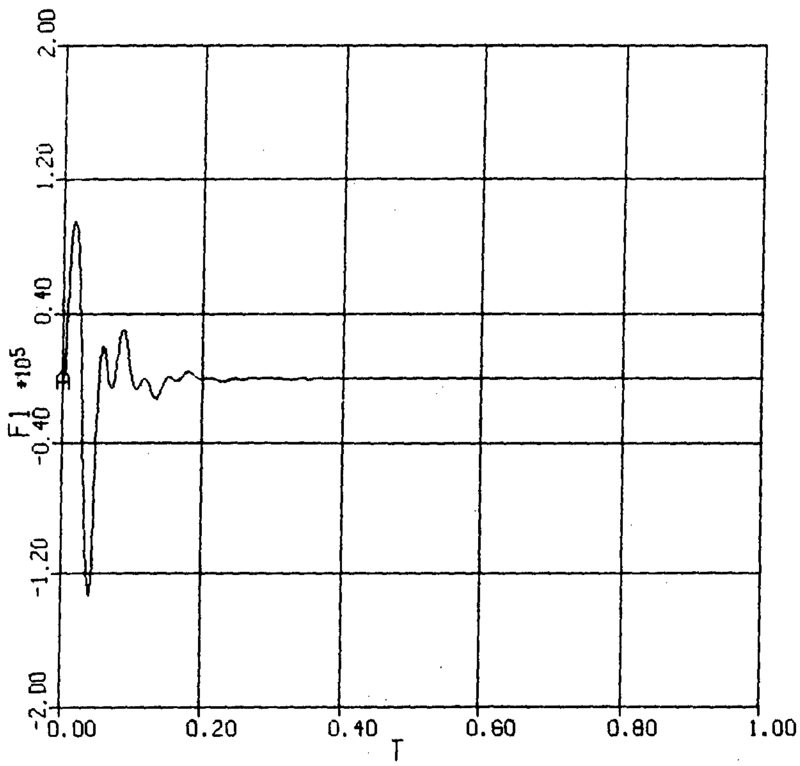


## STEP RESPONSE 1 IN

### ACTUATOR Δ Pressure




### ACTUATOR FORCE

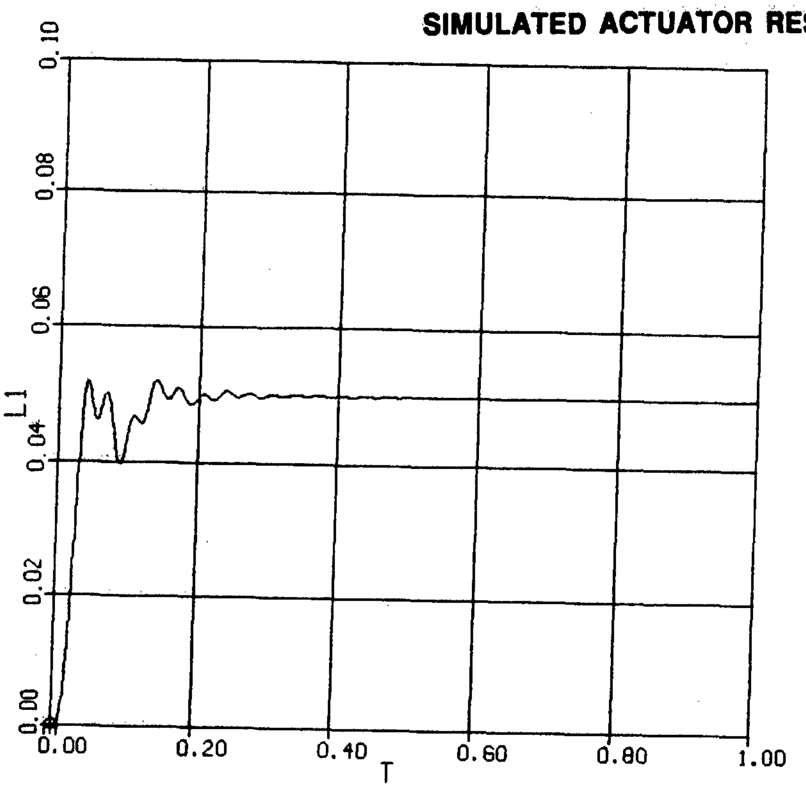


# APPENDIX D
# VARIED STEP RESPONSE RESULTS

## VARIED STEP RESPONSE

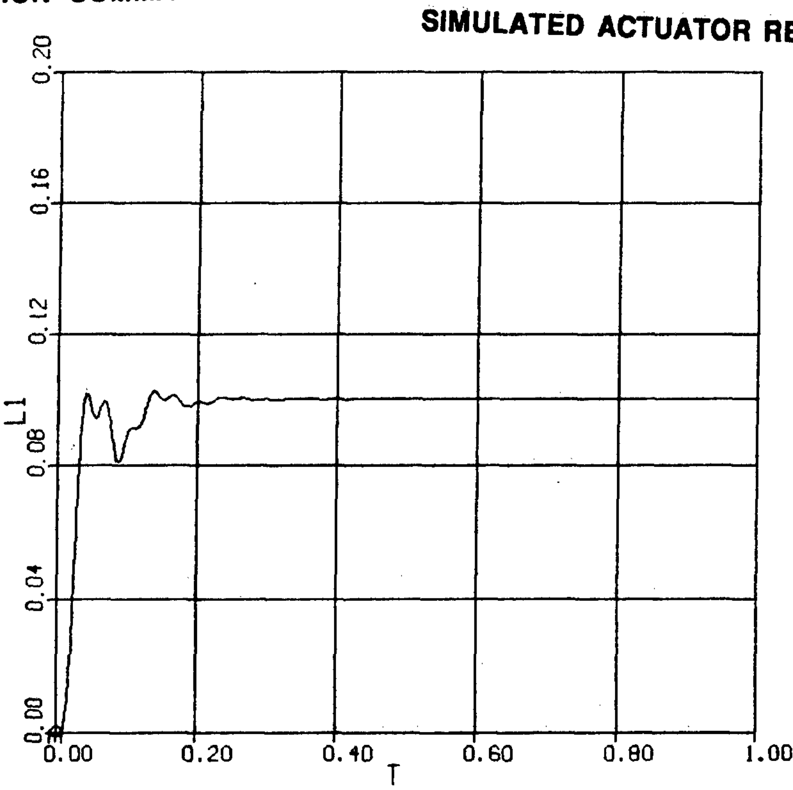
**POSITION COMMAND .05 IN**

**SIMULATED ACTUATOR RESPONSE**



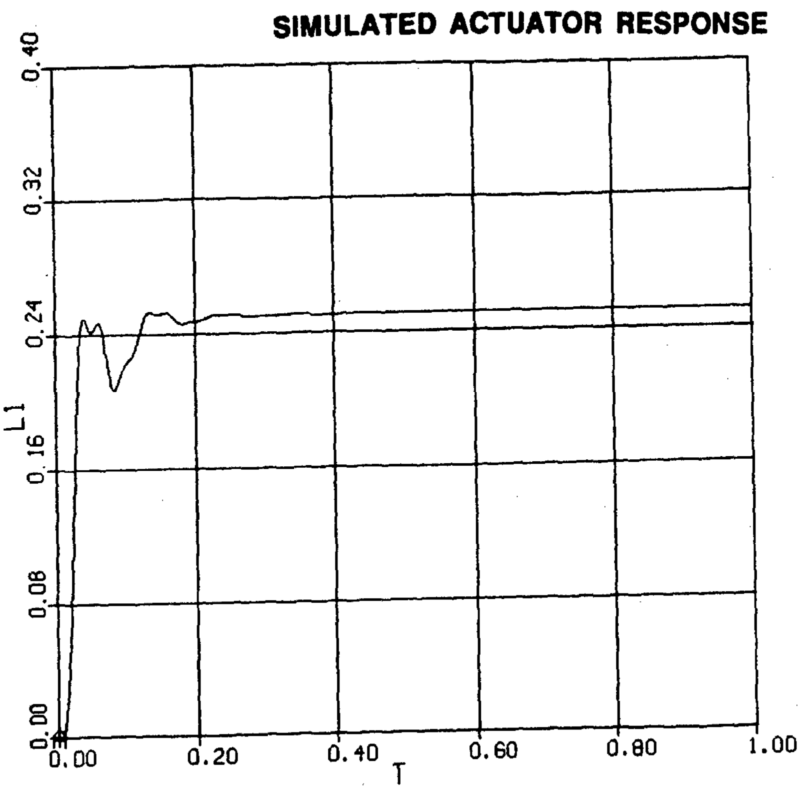

**POSITION COMMAND 0.1 IN**

**SIMULATED ACTUATOR RESPONSE**

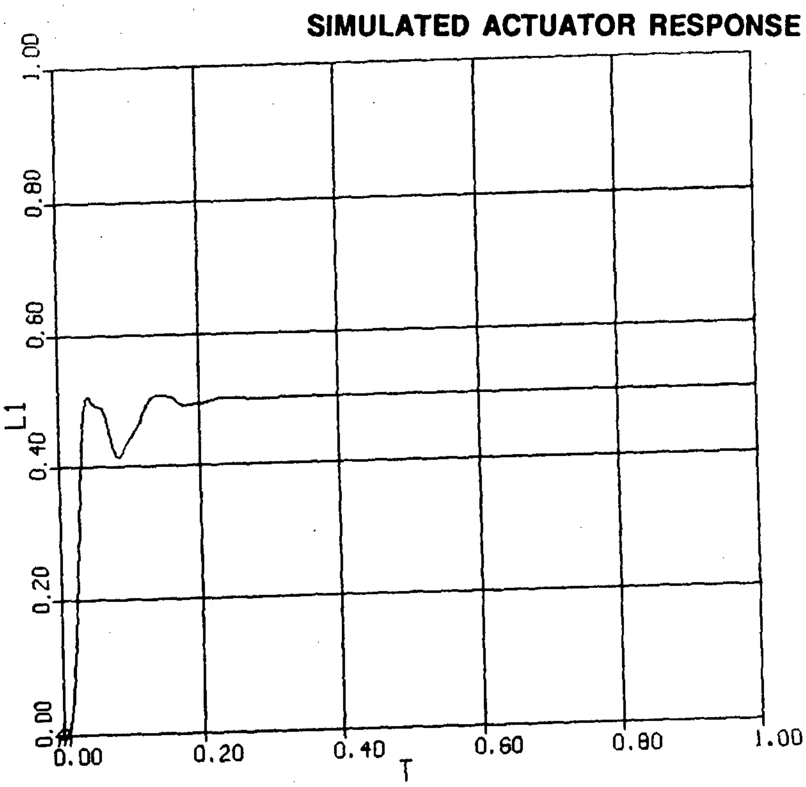


## VARIED STEP RESPONSE

**POSITION COMMAND 0.25 IN**

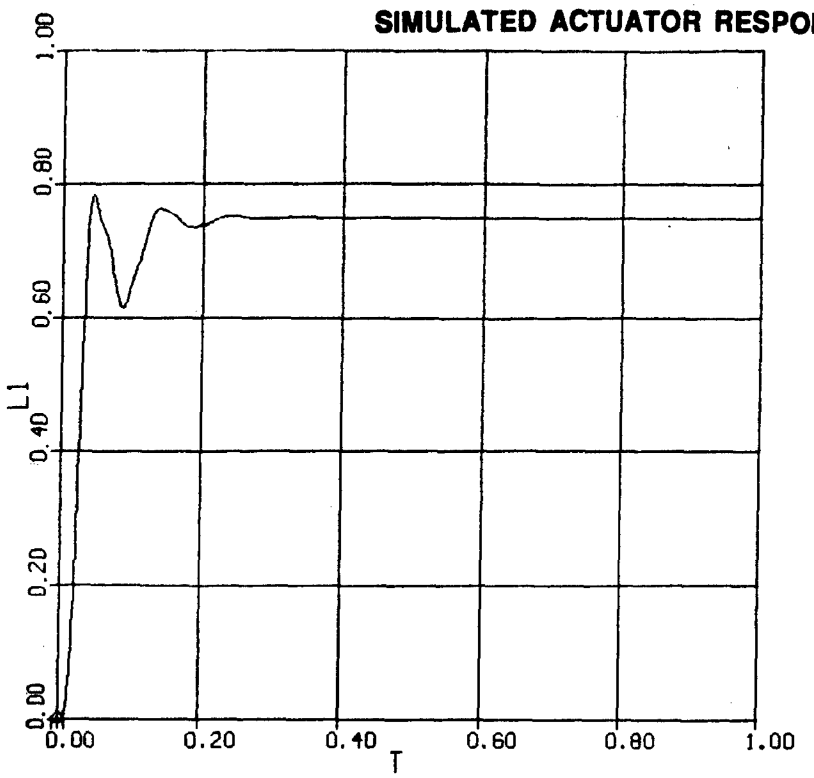



**POSITION COMMAND 0.5 IN**

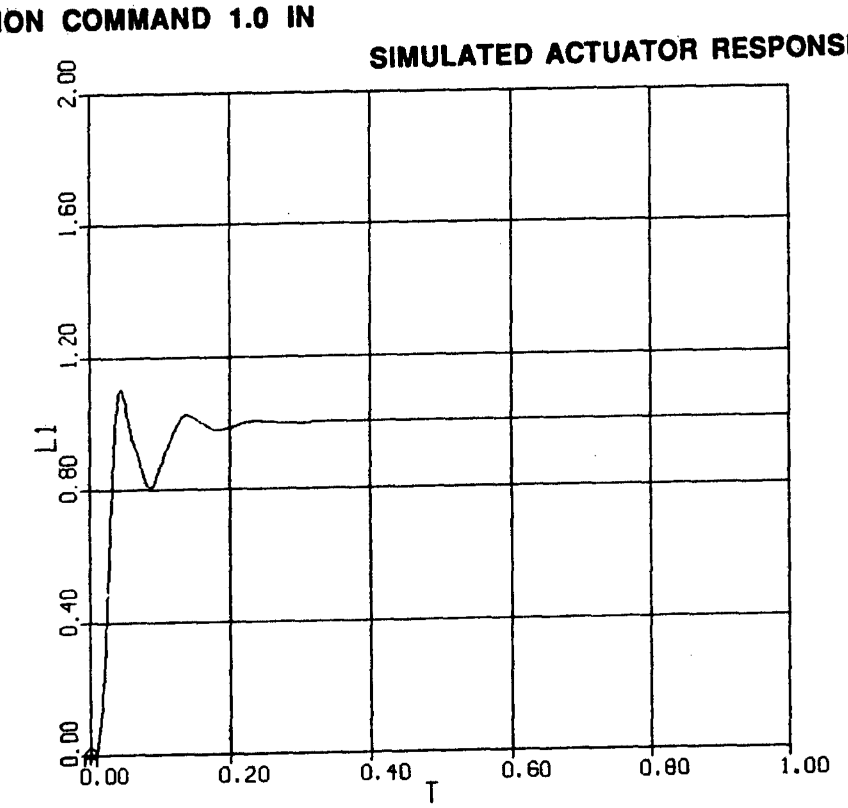


## VARIED STEP RESPONSE

**POSITION COMMAND 0.75 IN**



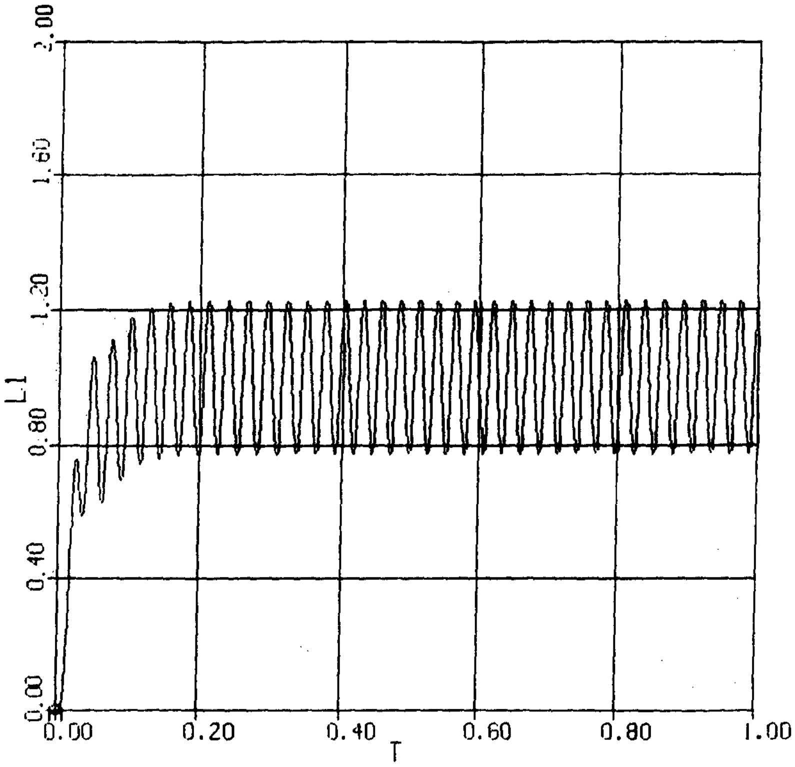

**POSITION COMMAND 1.0 IN**



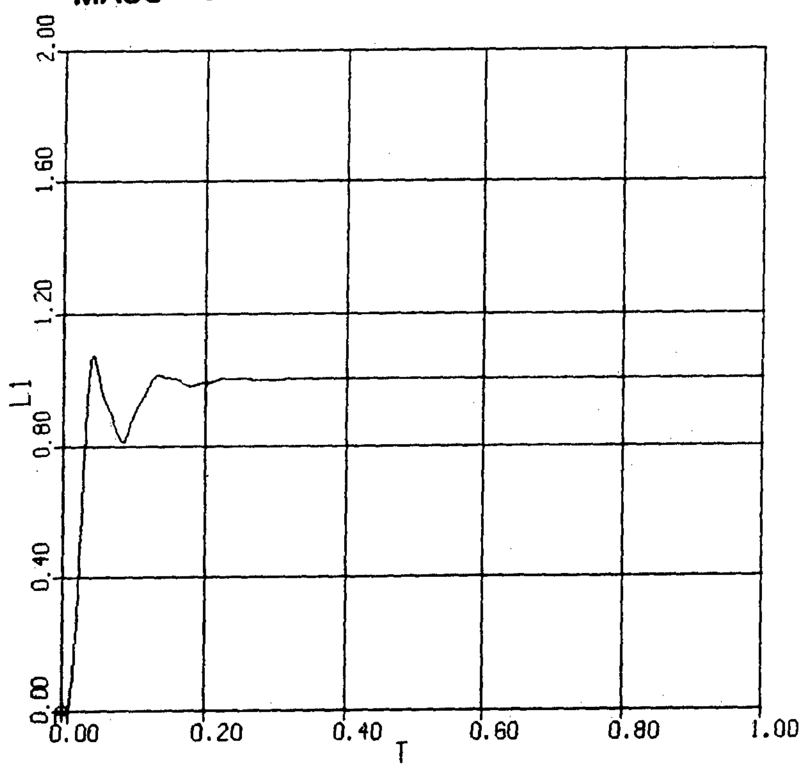
# APPENDIX E
# VARIED MASS RESULTS

## VARIED MASS 1 IN STEP RESPONSE

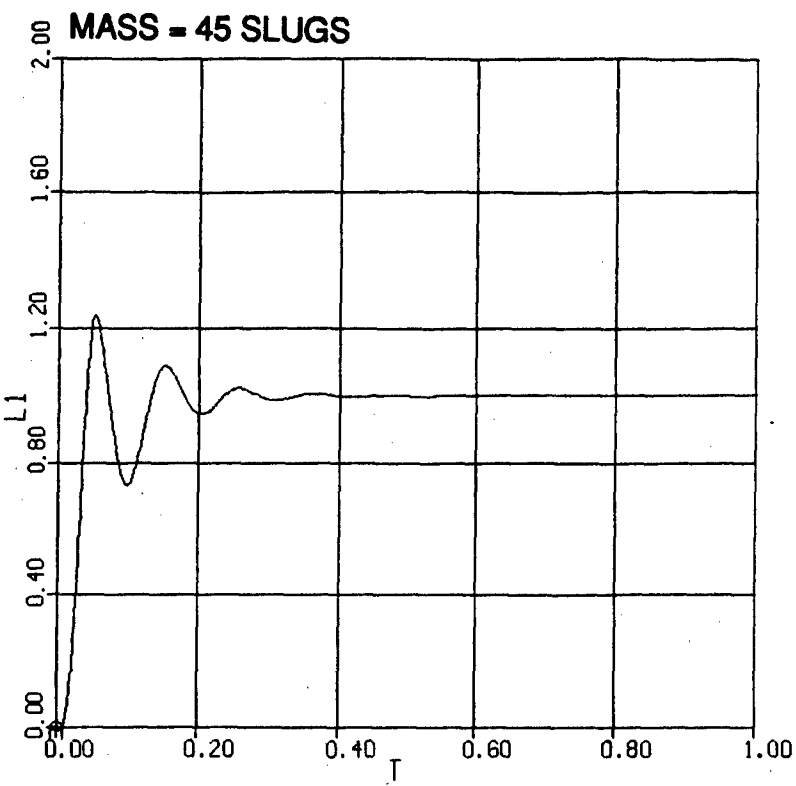
MASS = 10 SLUGS

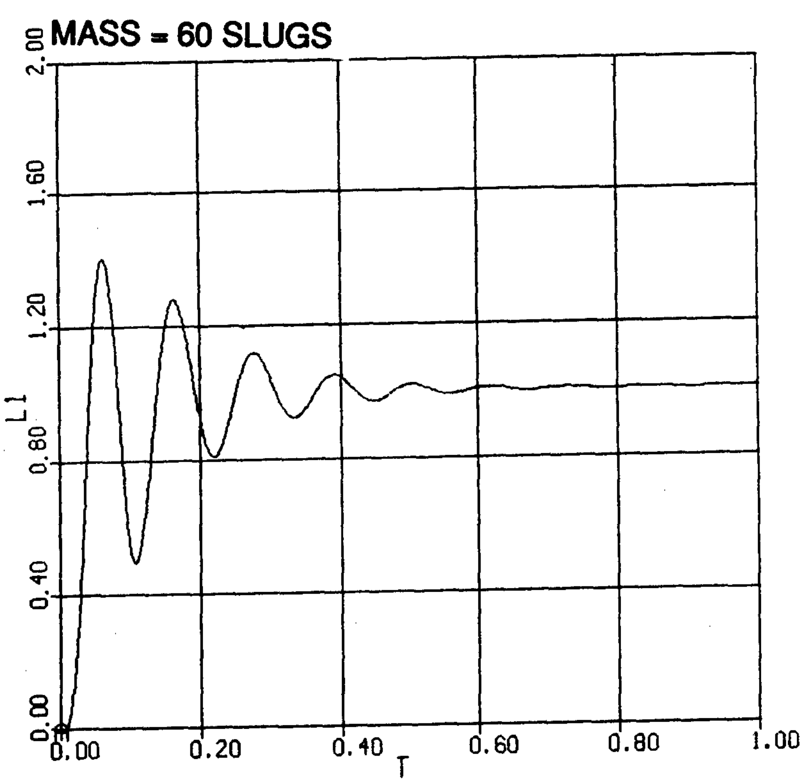



MASS = 30 SLUGS



# VARIED MASS 1 IN STEP RESPONSE



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